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Draft Environmental Impact Statement for 40 CFR Part 191: Environmental Standards for Management and Disposal of Spent Nuclear Fuel High-Level and Transuranic Radioactive Wastes

(U.S.) Office of Radiation Programs
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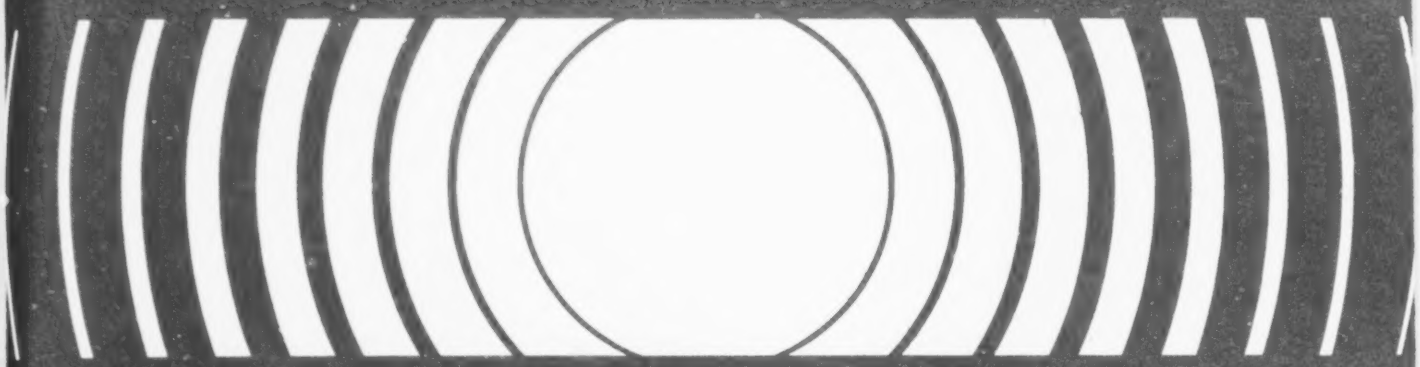

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16. ABSTRACT

The Environmental Protection Agency is proposing environmental standards for the management and disposal of spent nuclear reactor fuel and high-level and transuranic radioactive wastes. Subpart A of the standards would limit the radiation exposure of members of the public from management and storage of spent fuel and of waste prior to disposal. Subpart B would establish both quantitative containment requirements for disposal systems and qualitative requirements to assure that these containment requirements will be met. The containment requirements would limit the amount of radioactivity that may enter the environment for 10,000 years after disposal. The assurance requirements provide seven principles necessary for developing confidence that these long-term containment requirements will be complied with. These principles call for well-designed, multiple-barrier disposal systems that would not rely upon future generations for maintenance and would not be located near potentially valuable resources. They also require that future generations be provided information about the location and dangers of the wastes and an option to recover the wastes if they need to. In addition, Subpart B, contains procedural requiements to ensure that the containment requirements are properly applied. We think the proposed standards will adequately protect the public health and the environment, and we believe they can be satisfied without major economic consequences.

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40 CFR Part 191

ENVIRONMENTAL STANDARDS
FOR
MANAGEMENT AND DISPOSAL
OF
SPENT NUCLEAR FUEL, HIGH-LEVEL AND
TRANSURANIC RADIOACTIVE WASTES

DECEMBER 1982

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs

i.a

SUMMARY

DRAFT ENVIRONMENTAL IMPACT STATEMENT

40 CFR Part 191 Environmental Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes.

Prepared By:
Office of Radiation Programs
U.S. Environmental Protection Agency
December 1982

1. The Environmental Protection Agency is proposing environmental standards for the management and disposal of spent nuclear reactor fuel and high-level and transuranic radioactive wastes. Subpart A of the standards would limit the radiation exposure of members of the public from management and storage of spent fuel and of waste prior to disposal. Subpart B would establish both quantitative containment requirements for disposal systems and qualitative requirements to assure that these containment requirements will be met. The containment requirements would limit the amount of radioactivity that may enter the environment for 10,000 years after disposal. The assurance requirements provide seven principles necessary for developing confidence that these long-term containment requirements will be complied with. These principles call for well-designed, multiple-barrier disposal systems that would not rely upon future generations for maintenance and would not be located near potentially valuable resources. They also require that future generations be provided information about the location and dangers of the wastes and an option to recover the wastes if they need to. In addition, Subpart B contains procedural requirements to ensure that the containment requirements are properly applied. We think the proposed standards will adequately protect the public health and the environment, and we believe they can be satisfied without major economic consequences.

2. Copies of this Environmental Impact Statement and requests for comment have been sent to the following Federal agencies:

Department of Commerce
Department of Defense
Department of Energy
Department of Health and Human Services
Department of the Interior
Department of Transportation
National Aeronautics and Space Administration
Nuclear Regulatory Commission

We have also sent copies to all State Clearinghouses and to other individuals and organizations who have notified us of their interest.

3. Comments on this Environmental Impact Statement should be received by May 2, 1983. Please send comments (in duplicate if possible) to:

Central Docket Section (A-130)
Environmental Protection Agency
Attn: Docket No. R-82-3
Washington, D.C. 20460

4. For additional information, please contact Dan Egan at (703) 557-8610 or write to:

Director, Criteria and Standards Division
Office of Radiation Programs (ANR-460)
Environmental Protection Agency
Washington, D.C. 20460

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Chapter 1

OVERVIEW

Although high-level radioactive wastes are produced in small quantities, their proper management and disposal are important because of the inherent hazards of the large amounts of radioactivity they contain. This need for careful control has been recognized since the inception of the nuclear age. The Federal Government has always assumed responsibility for the ultimate care and disposal of high-level wastes, whether they are produced by commercial or national defense activities. Over the last several years, the Federal Government has intensified its program to develop and demonstrate a permanent disposal method for high-level wastes. President Reagan's April 28, 1982, message to Congress on nuclear waste disposal reaffirmed this commitment and called for a Federally owned and operated permanent repository to be available at the earliest practicable date. The environmental protection standards described in this Draft Environmental Impact Statement will provide the basic framework for the long-term control of these wastes.

The Agency is proposing these generally applicable environmental standards under authorities established by the Atomic Energy Act and transferred to the EPA by Reorganization Plan No. 3 of 1970. This Draft Environmental Impact Statement includes detailed discussions of major decisions and extensive summaries of our technical analyses. On November 15, 1978, the Agency proposed Federal radiation protection guidance for the disposal of all types of radioactive wastes (43 FR 53262).

After reviewing the public comments on that proposal, we decided that the characteristics of different kinds of radioactive waste are not sufficiently similar for generally applicable criteria to be appropriate. Therefore, we stopped developing this Federal radiation protection guidance (46 FR 17567). However, several of the principles included in this earlier proposal have been incorporated as integral parts of these environmental standards.

About 500 million curies of radionuclides with half-lives greater than 20 years exist in the wastes from reprocessing reactor fuel for national defense activities. These wastes are stored in various liquid and solid forms on three Federal reservations in Idaho, Washington, and South Carolina, respectively. Relatively small additions are being made from ongoing defense programs.

The total amount of spent fuel removed from commercial nuclear power reactors contains about 800 million curies of radionuclides with half-lives greater than 20 years. Over the next few years, this inventory is expected to grow at a rate of about 200 million curies per year from reactors currently licensed to operate. Virtually all of this spent fuel is stored at reactor sites. At some reactor sites, spent-fuel storage capacity is almost used up. Electrical utilities, the operators of commercial reactors, are pursuing a variety of techniques to increase storage capacities.

These proposed standards apply to spent reactor fuel, high-level wastes derived from reprocessing spent fuel, and wastes containing long-lived radionuclides of elements heavier than uranium (transuranic wastes). High-level wastes are covered by these standards if they contain concentrations of radioactivity greater than the limits recently set by the Nuclear Regulatory Commission (NRC) for acceptance at low-level waste disposal sites (47 FR 57446). Transuranic wastes are covered if they contain 100 nanocuries (one ten millionth of a curie) or more of alpha-emitting transuranic radionuclides per gram of waste. The proposed standards do not apply to wastes that have already been disposed of.

The objective of the proposed standards is to limit the risks to both present and future generations and to adequately protect the public from harm caused by management and disposal activities related to these radioactive wastes. Separate standards were developed for those activities related to waste management and storage operations preparatory to disposal (Subpart A) and for the long-term performance of disposal systems (Subpart B). The standards for management and storage are intended to protect exposed individuals while these operations are in progress. The standards for disposal are intended to assure long-term isolation of the hazardous wastes from the biosphere and protection of the public health.

The rationale for the standards for management and storage (Subpart A) is that these operations should not be permitted to substantially increase the risk to people beyond that now accepted for the normal operations of the uranium fuel cycle. We conclude that these added risks can be very small and that the exposure limits we have already established for the fuel cycle (40 CFR 190) can be extended to cover these additional operations. Therefore, the effect of Subpart A of the proposed standards is to apply the same requirements to the normal operations of all parts of the uranium fuel cycle, except transportation. Similar considerations apply to the management and storage of high-level and transuranic wastes from national defense activities, which are also covered by this Subpart.

The disposal standards (Subpart B) must deal with a yet unproven technology and with the need to extend public health protection far into the future. As our primary disposal standards, we are proposing containment requirements that place numerical limits on possible releases of radionuclides to the environment for 10,000 years after disposal. Although these requirements are not specific to any particular method of disposal, we focused on the use of mined geological repositories because more information is available on this technique. We performed detailed technical evaluations of the probabilities and consequences of possible events that could disrupt such a repository and cause release of a part of its contents. Our calculations show that the total adverse impact of releases of radionuclides from such a facility over 10,000 years can be kept very small and should be no greater than the risks from the unmined ore from which the wastes were derived. The proposed containment requirements--which would limit long-term risks to these low levels--apply to any method of disposal. Thus, any other method would have to provide at least as much protection as geologic disposal.

Because of the uncertainties inherent in projecting disposal system performance for 10,000 years, Subpart B also contains seven qualitative criteria that are needed to develop appropriate confidence that our containment requirements will be met. These assurance requirements set forth a cautious approach to disposal of these wastes, and they provide the context necessary for application of our containment requirements. The assurance requirements call for well-designed, multiple-barrier disposal systems that would not rely upon perpetual maintenance by future generations and that would be located where it is unlikely that they would be disturbed by natural forces or human activities. In addition, our disposal standards contain procedural requirements to ensure that the containment requirements are properly implemented.

We evaluated the effects of setting our containment requirements at different levels of protection. We found that the increased costs of setting these requirements at the proposed level could range from zero to 50 million (1981) dollars per year when compared to the costs of choosing a level more than 10 times less stringent (release limits 10 times greater than our proposed limits). This potential increase is much less than the uncertainty in the total costs for waste management and disposal, since these projected costs range from about 700 million to almost 1.5 billion (1981) dollars per year. For comparison, electrical utility revenues were about 100 billion dollars in 1980. We estimate that the potential economic impact of choosing the more stringent level of protection could be about a 0.2-percent increase in the costs of generating electricity from nuclear power plants and a much smaller increase (about 0.05 percent) in average electricity rates.

The standards for waste management and storage (Subpart A) will be implemented by the NRC for commercial nuclear power activities and by the Department of Energy (DOE) for national defense facilities. Implementation procedures for Subpart A will be similar to those for our Uranium Fuel Cycle standards (40 CFR 190). Our standards for disposal (Subpart B) will be implemented by NRC for all high-level wastes, whether the wastes come from commercial or military activities. NRC will develop the necessary regulations (primarily 10 CFR 60) and will issue appropriate construction and operating licenses to DOE. DOE will select, design, and build all disposal facilities for high-level wastes. Under current law, disposal of transuranic wastes from military activities is not regulated by NRC; therefore, DOE will apply our standards and guides to disposal of these transuranic wastes.

Chapter 2

THE PROPOSED ACTION

This Draft Environmental Impact Statement supports our proposed environmental standards for the management and disposal of spent nuclear fuel and high-level and transuranic radioactive wastes. It explains how we developed the proposed standards, examines alternative actions we could have taken, and discusses the related environmental impacts.

In this chapter we describe our proposed action. We identify the radioactive materials covered by these standards, how they are produced, their hazards, and how we can control them. We also explain the legal authorities under which these standards were developed. Finally, we summarize the various requirements we are proposing to protect public health and the environment. The complete text of our proposed environmental standards is contained in Appendix A.

2.1 HIGH-LEVEL WASTES

These proposed standards apply to the highly radioactive wastes resulting from reprocessing irradiated (spent) nuclear reactor fuel--and to the spent fuel itself if it is disposed of without reprocessing or if it is stored pending a determination on disposal. These wastes are products of the fission and activation processes associated with nuclear reactors. The reactors are used for commercial power production, research, and national defense activities. Other wastes containing large quantities or high concentrations of radioactivity, which may represent a significant danger to the public health if not properly handled, are not specifically included in these standards, but they may require similar considerations for disposal. Such wastes will be addressed as we work on environmental standards for disposal of other categories of radioactive waste.

High-level radioactive wastes from reprocessing have been commonly designated as the material remaining after recovery of uranium and plutonium from irradiated (spent) reactor fuel. These wastes include residual fissionable materials, fission products, and activation products. They may be in liquid or solid form, may be soluble or insoluble in water, and may emit any of several types of radiation over a wide range of energy.

Both spent fuel and high-level radioactive wastes from reprocessing are intensely radioactive and generate substantial quantities of heat. Radioactivity and heat production continue for long periods of time, because the wastes contain a number of long-lived radionuclides. The transuranium elements, especially, have long radiological half-lives and present a possible hazard to people for tens of thousands of years.

2.1.1 Commercial Reactor Wastes

The fuel used in the present generation of commercial light-water reactors consists of a mixture of uranium-238 and uranium-235 dioxides encased in zircalloy or stainless steel tubes. During reactor operation, fission of the uranium-235 produces energy, neutrons, and fission products.

The neutrons produce further fission reactions and thus sustain the chain reaction. The neutrons also convert some of the uranium-238 into plutonium-239, which can fission like uranium-235. In time, the fissile uranium-235, which originally constituted some 3 percent of the enriched fuel, is depleted to such a low level that power production becomes inefficient. Once this occurs, the fuel bundles are deemed "spent" and are removed from the reactor (an annual removal rate of 30 tons per reactor is typical).

Reprocessing of commercial spent fuel has been proposed with a view towards recovering the unfissioned uranium-235 and the plutonium for reuse as a fuel resource. However, spent fuel generated by commercial power reactors is not currently being reprocessed. The radioactive materials in spent fuel fall into two major categories: fission products and actinide elements. Typically, fresh spent fuel contains more than 100 radioactive nuclides as fission products. Fission products of particular importance, because of the quantities produced or their biological hazard, are strontium-90, technetium-99, iodine-129 and -131, the cesium isotopes 134, 135, and 137, tin-126, and krypton-85 and other noble gas isotopes. The actinides consist of uranium isotopes, transuranic elements (i.e., isotopes with atomic number greater than 92, including plutonium-239, americium-241 and -243, and neptunium-237) formed by neutron capture, and their decay products. Spent fuel also contains tritium (hydrogen-3), carbon-14, and other radioactive isotopes created by neutron activation. The exact composition of radionuclides in any given spent-fuel sample depends on the reactor type, the initial fuel composition, the length of time the fuel was irradiated, and the elapsed time since its removal from the reactor core.

If fuel is reprocessed, the resulting waste is an acidic aqueous solution containing most of the actinides and the nonvolatile fission products present in the fuel. About 0.5 percent of the original uranium and plutonium would be left in the waste liquid. Current Federal regulations require that commercial high-level liquid waste be converted to a solid within 5 years. Calcination is the best available solidification process. The calcined waste should be converted to a more stable form for ultimate disposal.

The inventory of spent fuel through 1980 was about 7000 metric tons of heavy metal (DOE 81). The activity of this spent fuel depends heavily on its age, since fresh spent fuel contains large quantities of short-lived fission products. By calculating waste activities as of 10 years after removal from the reactor, one can largely eliminate the variability due to short-lived fission products. On this basis, the activity of the 7000 metric tons of spent fuel corresponds to over 2 billion curies. A small amount of commercial fuel has been reprocessed, producing about 600,000 gallons of liquid waste (EPA 80) containing about 30 million curies (BNWL 76).

Predictions of high-level waste production from commercial generation of electrical power depend on estimates of the growth of the nuclear power industry. The Interagency Review Group (IRG 79) estimated a range of cumulative totals by the year 2000 of about 70,000 to 100,000 metric tons of spent fuel, corresponding to 148 and 380 gigawatt-electric (GWe) of installed capacity, respectively. Arthur D. Little (ADL 79) developed an upper estimate of 700 GWe of installed capacity by the year 2010, for 500,000 metric tons of spent fuel containing about 200 billion curies.

2.1.2 Defense Wastes

Weapons program reactors are operated to produce plutonium; reprocessing to recover the plutonium is an integral part of the weapons program operations. Naval propulsion reactor fuel elements are also reprocessed to recover the highly enriched uranium they contain.

The present inventory of defense wastes in the U.S. is about 290,000 cubic meters (10 million cubic feet or 70 million gallons), stored at three Federal reservations as liquids, sludges, and solids (IRG 79). Operation of the weapons program reactors and other defense activities will continue to produce defense wastes. Table 2-1 gives projections of both the quantity and radioactivity of high-level defense wastes (ADL 79).

Table 2-1

Defense High-Level Waste Projections

	Volumes	Radioactivity (Ci)		
Site	Cubic Meters	Total Fission Products	Uranium	Transuranics
Hanford[a]	200,000	2.5×10^8	710	1.4×10^5
Savannah River[b]	83,000	3.2×10^8	48	7.4×10^5
Idaho[a]	11,000	1.0×10^8	2	1.0×10^3
TOTAL	294,000	6.7×10^8	760	8.8×10^5

(a) 1990 waste projection.
(b) 1985 waste projection.

2.1.3 Definition of High-Level Wastes in 40 CFR 191

In developing its regulations for disposal of high-level wastes in geologic repositories (10 CFR 60), the Nuclear Regulatory Commission (NRC) defined high-level wastes as (NRC 81b):

> ". . . (1) irradiated reactor fuel, (2) liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel, and (3) solids into which such liquid wastes have been converted."

For the purposes of our environmental standards, we are proposing a somewhat different definition of high-level wastes:

> ". . . any of the following that contain radionuclides in concentrations greater than those identified in Table 1: (1) liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, in a facility for reprocessing spent nuclear fuels; (2) the concentrated wastes from subsequent extraction cycles, or equivalent; (3) solids into which such liquid wastes have been converted; or (4) spent nuclear fuel if disposed of without reprocessing.

There are two substantive differences between our definition and the one in 10 CFR 60. The first is that our definition does not identify spent nuclear fuel as a waste unless it is determined that such fuel will be disposed of without reprocessing. Thus, provisions of our standards that specifically apply to waste would not apply to spent fuel until such a determination was made.

The other major difference is that our definiton of high-level waste excludes materials with concentrations of radioactivity below those in Table 2-2 (which reproduces Table 1 of the proposed standards).

Table 2-2:

Concentrations Identifying High-Level Radioactive Wastes

(Table 1 in 40 CFR Part 191)

Radionuclide	Concentration (curies per gram of waste)
Carbon-14	8×10^{-6}
Cesium-135	8×10^{-4}
Cesium-137	5×10^{-3}
Plutonium-241	3×10^{-6}
Strontium-90	7×10^{-3}
Technetium-99	3×10^{-6}
Tin-126	7×10^{-7}
Any alpha-emitting transuranic radionuclide with a half-life greater than 20 years	1×10^{-7}
Any other radionuclide with a half-life greater than 20 years	1×10^{-3}

NOTE: In cases where a waste contains a mixture of radionuclides, it shall be considered a high-level radioactive waste if the sum of the ratios of the radionuclide concentration in the waste to the concentration in Table 1 exceeds one.

For example, if a waste contains radionuclides A, B, and C in concentrations C_a, C_b, and C_c and if the concentration limits from Table 1 are CL_a, CL_b, and CL_c, then the waste shall be considered high-level radioactive waste if the following relationship exists:

$$\frac{C_a}{CL_a} + \frac{C_b}{CL_b} + \frac{C_c}{CL_c} \geqslant 1$$

We propose to make this exclusion because some wastes derived from reprocessing spent fuel may not require the same isolation as the wastes containing most of the radioactivity produced in the fuel. In particular, processing of certain high-level wastes from national defense activities may remove much of the radioactivity, leaving residual material that is far less dangerous (for example, large volumes of salt cake containing relative low concentrations of technetium-99). Our definition would allow such material to be disposed of without having to meet the stringent requirements we feel are appropriate for the most highly radioactive wastes. The disposal requirements for materials excluded by our definition will be addressed as we develop standards for low-level radioactive wastes.

The levels in Table 2-2 are equivalent to the maximum concentrations for acceptance at shallow-land burial sites that the NRC recently promulgated as part of 10 CFR Part 61 (47 FR 57446). The NRC derived the concentration limits in 10 CFR 61 so that a person intruding into a shallow-land site--after institutional controls were no longer effective--should not receive a radiation exposure greater than 500 millirem per year (NRC 81a and WI 81). We converted the units of these concentrations from curies per unit volume to curies per unit mass by assuming a density of 1 gram per cubic centimeter. For wastes with higher densities, the levels in Table 2-2 would be somewhat more stringent than the levels in 10 CFR 61.

2.2 TRANSURANIC WASTES

The proposed standards also apply to wastes containing alpha-emitting transuranic nuclides with half-lives greater than 1 year at concentrations greater than 100 nanocuries per gram (nCi/g). Alpha-emitting transuranic nuclides represent a special type of hazard because of their long half-lives and high radiotoxicity. Cohen and King (CO 78) considered the levels at which these materials might require handling different than that generally given to low-level radioactive wastes. They concluded that the more hazardous transuranic elements could cause excessive radiation doses if they are present at concentrations of about 1 microcurie per cubic centimeter of waste. A task group (HE 79) recommended shallow-land burial for Department of Energy (DOE) transuranic wastes with concentrations below 1 to 10 nCi/g. The task group also suggested that somewhat deeper burial was suitable for transuranic wastes with concentrations up to 100 nCi/g. In view of these studies, transuranic wastes with concentrations above 100 nCi/g were included under these standards.

There are about 1100 kilograms of transuranic elements at levels above 10 nCi/g in defense wastes at DOE facilities (IRG 79). These radionuclides are contained in about 400,000 cubic meters (14 million cubic feet) of transuranic-contaminated wastes. Both the DOE and the EPA have studies underway to define the amounts and characteristics of defense transuranic wastes containing more than 100 nCi/g.

2.3 BIOLOGICAL EFFECTS OF RADIATION

Radioactive materials may emit particulate (alpha and beta) or electromagnetic (gamma and X) radiation that can interact with matter. In this interaction, energy is transferred from the radiations to the matter. Energy transferred to matter is called absorbed dose. The unit of dose is the rad (ICRU 71), which corresponds to the absorption of 100 ergs per gram of material (0.01 joules per kilogram).

Gamma radiation, X-rays, and beta particles are sparsely ionizing radiations, with low linear energy transfer (low-LET). Alpha particles, such as those emitted by transuranic radionuclides, are high-LET radiations that exhibit a very dense ionization pattern in tissue. The interaction of radiation with living tissue in man, animals, or plants may damage the tissue. Since the absorption of the same quantity of energy from different radiations can produce different biological effects in living tissue, modifying factors are applied for the nature of the radiation and other considerations. The product of the dose and the modifying factors is called the dose equivalent (ICRU 73); the unit of dose equivalent is the rem. The total impact on a population is the population dose equivalent, the sum of the radiation dose equivalent incurred by each person in the population.

Releases of high-level wastes to the environment may cause human exposure from direct radiation or from breathing or ingesting radionuclides. These modes of exposure may arise because of volatilization, particulate dispersion, and dissolution of the waste materials--the predominant pathway(s) depend on the mode of release, the specific environmental circumstances, and the isotopic composition of the released material.

Exposure to large amounts of radiation, on the order of tens to hundreds of rems, in a short time (acute exposure) can produce a number of effects on humans ranging from barely detectable to severe. These effects range from chromosome and blood cell changes through loss of appetite and loss of hair, to diarrhea, vomiting, and even death. The severity of the effect is directly related to the amount of radiation absorbed by the individual.

Releases from a high-level waste repository, if they occur at all, are expected to be much smaller than those that would cause acute effects. These continuing (chronic) exposures to radiation, at levels well below those noted in the preceding paragraph, have no detectable early effects. However, in such cases, there may be delayed effects. The major delayed effects are the development of cancer and the production of genetic changes. In contrast to acute effects, for which the severity depends on the dose equivalent incurred, delayed effects develop only in some of the exposed individuals. The rate of incidence is a statistical function and depends on the total population dose equivalent incurred.

The relationship between the radiation dose and the number of delayed health effects has been studied extensively. The National Academy of Sciences (NAS 72 and 80) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UN 77) have published reviews of the current state of knowledge on this subject. Because of the inherent uncertainties in our scientific evidence, and as a prudent general policy for public health protection, we use a linear, non-threshold relationship between radiation dose and the risk of incurring cancer or genetic abnormalities. This relationship assumes that any exposure can produce some harm and that the harm is proportional to the absorbed dose. For the low dose rates considered here, this assumption may overestimate the risk from low-LET radiation. Because no method of disposing of hazardous materials can be entirely free of risk, the development of standards limiting the level of risk cannot be based solely on health considerations. The extent to which risk can reasonably be reduced, considering social, economic, and other factors, must also be evaluated.

2.4 METHODS OF CONTROL

Protection of humans from the hazards of radioactive wastes requires shielding or permanent physical separation of wastes from people. Specially designed storage facilities may provide short-term protection, but long-term protection must rely on passive natural and engineered barriers requiring no upkeep during their entire functional lifetime. (Conceivably, the wastes could be removed entirely from the biosphere by transport away from the earth or by transmutation to less harmful materials, but these alternative concepts do not currently appear practical.)

Subpart A of the proposed standards applies to the management, including storage, processing, and emplacement, of the wastes, but it does not cover their offsite transportation. Subpart B applies to the wastes after disposal. For a geologic repository, for example, Subpart B would take effect when the mine is backfilled and sealed.

2.4.1 Storage of Spent Fuel and High-Level Wastes

There is considerable experience with storing spent fuel. Fuel elements are kept in racks in water basins to remove the heat and provide shielding. Dry, air-cooled storage of aged spent fuels, which produce less heat than fuels recently removed from a reactor core, has been proposed.

There is also considerable experience with storing liquid wastes from the reprocessing of spent fuel, since most defense wastes are of this nature. Most of these acidic liquids have been neutralized for storage in large steel tanks. A small fraction of these existing liquid wastes has leaked from the tanks, requiring transfer into new tanks. Liquid wastes can be converted to solids, which are then stored like spent fuel.

2.4.2 Disposal in Mined Repositories

Development work on methods for disposal of spent fuel and solidified high-level and transuranic radioactive wastes has concentrated on mined geological repositories. Such repositories would be constructed at depths greater than 1000 feet by using conventional mining techniques in suitable host media. Suggested media include granite, basalt, volcanic tuff, and salt. Wastes in canisters would be placed in holes in the mine floor. When the repository is full, it would be backfilled. After a validation period, during which the wastes could be retrieved, the site would be permanently sealed. Protection would be provided by a stable and insoluble waste form, a durable canister, a stable host medium, and low migration potential for radionuclides through the environment around the host rock. Mined geological repositories are expected to be available for use sooner than any other disposal method.

2.4.3 Other Disposal Methods

A number of other methods have been suggested for disposal of high-level radioactive wastes. These methods include:

- -- Placement of fresh liquid or solid wastes directly into rocks by melting. The heat of the fresh wastes would melt the rock, and the wastes would become incorporated as an integral component of that rock.
- -- Placement of containers of waste into holes 10,000 to 30,000 feet deep.

-- Placement of containers of high-level wastes on or under the ocean floor. Disposal of high-level wastes in the ocean is prohibited under United States law by the Marine Protection, Research, and Sanctuaries Act of 1972.

-- Transport into space (extraterrestrial disposal) or transmutation in fission or fusion reactors of the most long-lived or hazardous radionuclides. Both of these methods would dispose of only a portion of the wastes, leaving the rest for disposal on earth.

These alternative methods of disposal are discussed in more detail in Chapter 3.

2.5 AUTHORITIES

Reorganization Plan No. 3 of 1970 transferred to EPA two functions derived from the Atomic Energy Act of 1954: (1) the responsibilities of the former Federal Radiation Council, and (2) the authority to set generally applicable environmental standards. The authority to set generally applicable environmental standards was transferred from the Atomic Energy Commission:

> ". . . to the extent that such functions of the Commission consist of establishing generally applicable environmental standards for the protection of the general environment from radioactive material. As used herein, standards mean limits on radiation exposures or levels, or concentrations or quantities of radioactive material, in the general environment outside the boundaries of locations under the control of persons possessing or using radioactive material."

Our generally applicable environmental radiation standards are rules that apply outside the controlled boundaries of facilities using radioactive materials. They are designed to preserve the general environment and protect the public health. The NRC--or in some cases the DOE--implements and enforces these standards by issuing specific regulations and by assuring that individual and interrelated components of the fuel cycle are constructed and operated consistent with licensing provisions and all applicable regulations.

The authorities inherited from the former Federal Radiation Council, under Executive Order 10831 and the Atomic Energy Act (42 U.S.C. 2021(h)), include the responsibility to:

> ". . . advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance to Federal agencies in the formulation of radiation standards . . ."

We provide advice by preparing Federal radiation protection guidance for approval by the President as executive direction to Federal agencies. These guides establish overall direction for the radiation protection programs of all Federal agencies. Executive Order 12088 makes the head of each agency responsible for compliance with such guides, once the President has approved them. In addition, the Order directs the EPA to monitor compliance by Federal agencies. Conflicts on implementation may be resolved by the Director of the Office of Management and Budget. Exemptions from the guides may be granted by the President.

The environmental protection requirements described in this Draft Environmental Impact Statement are proposed solely under our generally applicable environmental standards authority. However, we considered alternatives to our proposed action that would involve our Federal radiation protection guidance authority. These alternatives are discussed in Chapter 4.

2.6 THE PROPOSED STANDARDS

We are proposing generally applicable environmental standards for both the management and the disposal of spent fuel, and high-level and transuranic radioactive wastes. When promulgated, these standards will become a new Part 191 to Title 40 of the Code of Federal Regulations (40 CFR 191). Subpart A applies to all operations up to and including the emplacement of the wastes in a disposal system. Subpart B applies to the period after disposal, except that these standards would not apply to disposal directly into the oceans or ocean sediments. Both Subparts are summarized below; they are examined in more detail in Chapters 6 and 7 of this document.

2.6.1 Standards for Management and Storage (Subpart A)

The preparation for disposal or storage of these materials and the placement of the materials in a disposal system are included under these standards. The transportation of the materials is not covered. These standards for waste management and storage operations apply only to anticipated normal events or releases.

Most of the wastes subject to this regulation (40 CFR 191) were and will be derived from the production of commercial nuclear power and from activities in national defense programs. We have issued regulations (40 CFR 190) covering one aspect of nuclear power production--the uranium fuel cycle--from milling of ore through the generation of electricity at a nuclear power plant and the reprocessing of spent uranium fuel. The 40 CFR 191 regulations proposed here ideally should include all operations following those covered in 40 CFR 190 up to and including the final abandonment of the waste materials. In this way, no portion of the uranium fuel cycle subsequent to mining (which is not included under the authority of the Atomic Energy Act of 1954, as amended) would be left uncontrolled. Waste management problems in national defense programs, and in other projected or contemplated fuel cycles, are similar enough to those in the uranium fuel cycle that they can also be included under 40 CFR 191. The storage of spent fuel, whether or not it has been designated as a waste material, is included in this regulation when such storage is not already regulated under 40 CFR 190.

We examined the radiation exposure to members of the public from waste management and storage prior to geologic disposal and determined that it is feasible, with available technology and proper siting of facilities, to limit maximum individual doses from all normal operations to those dose limits established for uranium fuel cycle operations in 40 CFR 190. Those limits are 25 millirem to the whole body, 75 millirem to the thyroid, and 25 millirem to any other organ. Therefore, we propose to extend the limitations of 40 CFR 190 to the operations covered by 40 CFR 191. Since some of these operations can be conducted with individual doses significantly lower than these limits, Subpart A also requires that exposures be reduced below these limits to the extent reasonably achievable, taking into account technical, social, and economic considerations.

These limitations for individual exposures from waste management operations do not include transportation of spent fuel or high-level and transuranic wastes. Normal exposures in transportation would be in the direct radiation to persons near shipments; radioactive materials could be released only due to accidents. Transportation of spent fuel was considered in the development of the Uranium Fuel Cycle (40 CFR 190) standards. We found that the average radiation dose to individuals and the total dose to the general public were small for transportation activities in the uranium fuel cycle. It is unlikely that an individual would receive an annual exposure greater than 25 millirem from exposure to shipments. We concluded, however, that providing a regulatory guarantee that no individual could receive annual doses greater than 25 millirem would be extremely difficult because of the problems involved with identifying and monitoring individual exposures. The expected risks from transportation of high-level wastes are similarly small. Thus, it is inappropriate to include transportation under these standards.

2.6.2 Standards for Disposal (Subpart B)

The intent of disposal is to isolate the wastes from the environment for a long time without the need for human intervention. Therefore, the standards for a disposal system can be implemented only through general planning and selection criteria and by designing the system to meet projected performance requirements.

The proposed standards for disposal apply to both normal and accidental releases, and both types of events must be considered by those who will design and license a repository. The most significant releases may result from unplanned or accidental events or processes. These accidental releases would occur long after the conclusion of normal operations at the disposal site. A release may be undetected for long periods of time, and there may be no way to correct the situation. There may be no personnel on hand to take protective actions, and the very concept of the site as a place under control of an organization may be inappropriate. Addressing the problem of unplanned releases is, therefore, a prime requirement of the proposed standards for disposal.

The proposed standards for disposal contain numerical containment requirements for the first 10,000 years after disposal, accompanied by qualitative requirements to assure that these containment requirements are met. These two parts of our proposed action are complementary: the containment requirements set limits on potential releases of radioactive materials to the environment--limits that will serve as overall design objectives for disposal systems; the assurance requirements provide the framework necessary to develop appropriate confidence in meeting these projected release limits in spite of the inherent uncertainties of predictions over 10,000 years. In addition, the proposed standards contain procedural requirements to ensure that the containment requirements are properly applied to specific disposal systems.

Containment Requirements

As our primary environmental protection standards, we are proposing numerical limits on the projected maximum amount of radioactivity a disposal system can release to the environment. These requirements would apply to both expected and accidental releases that could occur within 10,000 years after waste disposal. They place a limit on the harm that a disposal system can cause to future generations.

For high-level wastes, the release limits are expressed as the maximum amounts of radioactivity that can be released from disposal of the wastes generated from 1000 metric tons of heavy metal (MTHM). For transuranic wastes, the release limits are expressed as the maximum amounts of radioactivity that can be released from disposal of transuranic wastes containing 1 million curies of alpha-emitting transuranic radionuclides. These units were chosen so that the standards would require alpha-emitting radioactivity from either high-level or transuranic wastes to be isolated with about the same degree of effectiveness.

To determine the potential harm to future generations from waste disposal, we studied the projected environmental impacts of high-level waste disposal in mined geologic repositories. Our studies were based on the potential releases from a generic model of a repository containing 100,000 MTHM as spent reactor fuel. This is about as much waste as would be generated during the 40-year operating lifetimes of 100 large reactors of current design. We examined the risks over the first 10,000 years after disposal.

As a basis for comparison, we also evaluated other sources of radiation exposures to present and future generations. We looked at the radiation risks from natural background radiation, from unmined uranium ore bodies (the initial source of these wastes), from commercial nuclear power generation, and from fallout from previous atmospheric testing of nuclear weapons.

Based on these analyses and evaluations, we decided we could choose performance requirements that would satisfy two objectives:

First, the requirements would limit the harm to future generations to no more than 1000 excess cancer deaths over 10,000 years (an average of one extra death every 10 years) from disposal of the wastes from 100,000 MTHM. This risk is about the same as our smallest estimate of the harm from an equivalent amount of unmined uranium ore, and it is much smaller than the risks from the other sources of radiation exposure that we studied.

Second, the requirements appear to be achievable by well designed geologic repositories at carefully selected sites. Any other method used would have to provide at least as much protection as that projected for geologic disposal.

Once we chose this level of protection as a basis for these standards, we developed a set of numerical release limits for the various radioisotopes in the wastes. We estimated how many curies of each radioisotope would cause 1000 deaths over 10,000 years if it were the only radionuclide released; this number of curies determined the release limit for that radionuclide. For releases involving more than one radionuclide, the allowed release for each radionuclide is reduced to a fraction of its limit to assure the overall limit on harm is not exceeded. The procedure for using the release limits is described in Table 2 of the proposed standards (see Appendix A of this document).

Assurance Requirements

Closely associated with our numerical containment requirements are seven qualitative requirements we believe are essential for developing the needed confidence that these long-term release limits will be met. Our assurance requirements address and compensate for the uncertainties that necessarily accompany plans to isolate high-level and transuranic wastes from the environment for a very long time. No matter how promising analytical projections of disposal system performance appear to be, these wastes should be disposed of in a cautious manner that reduces the likelihood of unanticipated releases. Our assurance requirements provide the context necessary for application of our containment requirements, and they should insure very good long-term protection of the environment.

Several of the concepts incorporated in these assurance requirements were adapted from the Federal radiation protection guidance for all types of radioactive waste disposal that we proposed for public comment on November 15, 1978 (43 FR 53262). After reviewing the responses we received, we decided that the characteristics of different kinds of radioactive waste are not sufficiently similar for generally applicable criteria to be appropriate. Therefore, we stopped developing this Federal radiation guidance (46 FR 17567). However, we also determined that, because of the uncertainties inherent in meeting our 10,000-year containment requirements, several of the principles included in this earlier proposal needed to be incorporated as integral parts of these standards for disposal of high-level and transuranic wastes.

We expect that the specific steps taken by the NRC or the DOE to comply with each of these seven assurance requirements will be described in the Federal environmental impact statement--and other appropriate decision documents--for each disposal system. These seven requirements are:

1. Wastes shall be disposed of promptly once disposal systems are available and the wastes have been suitably conditioned for disposal.

2. Disposal systems shall be selected and designed to keep releases to the accessible environment as small as reasonably achievable, taking into account technical, social, and economic considerations.
3. Disposal systems shall use several different types of barriers to isolate the wastes from the accessible environment. Both engineered and natural barriers shall be included. Each such barrier shall separately be designed to provide substantial isolation.
4. Disposal systems shall not rely upon active institutional controls to isolate the wastes beyond a reasonable period of time (e.g., a few hundred years) after disposal of the wastes.
5. Disposal systems shall be identified by the most permanent markers and records practicable to indicate the dangers of the wastes and their location.
6. Disposal systems shall not be located where there has been mining for resources or where there is a reasonable expectation of exploration for scarce or easily accessible resources in the future. Furthermore, disposal systems shall not be located where there is a significant concentration of any material which is not widely available from other sources.
7. Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.

Procedural Requirements

The containment requirements were derived with the assistance of our performance assessments of long-term repository performance (summarized in Chapter 5). When these requirements are applied to a particular disposal system, some of the procedures we used in our assessments must be retained to ensure that the intent of our containment requirements is met. On the other hand, some of the assumptions we made should be replaced with the specific information developed for each particular system. Our three procedural requirements provide instructions necessary for performance assessments of specific disposal systems to properly demonstrate compliance with our containment requirements:

1. The assessments shall consider realistic projections of the protection provided by all of the engineered and natural barriers of a disposal system.
2. The assessments shall not assume that active institutional controls can prevent or reduce releases to the accessible environment beyond a reasonable period (e.g., a few hundred years) after disposal. However, it should be assumed that the Federal Government is committed to retaining passive institutional control of disposal sites in perpetuity. Such passive controls should be effective in deterring systematic or persistent exploitation of a disposal site, and it should be assumed that they can keep the chance of inadvertent human intrusion very small as long as the Federal Government retains such passive control of disposal sites.

3. The assessments shall use information regarding the likelihood of human intrusion, and all other unplanned events that may cause releases to the accessible environment, as determined by the implementing agency for each particular disposal site.

2.7 IMPLEMENTATION

The standards for waste management and storage (Subpart A) will be implemented by the NRC for commercial nuclear power activities and by the DOE for national defense facilities. Implementation procedures for Subpart A will be very similar to those for the Uranium Fuel Cycle Standards (40 CFR 190).

The standards for disposal (Subpart B) will be implemented by the NRC for all high-level wastes, whether the wastes come from commercial or national defense activities. The NRC will do this by developing the necessary regulations (primarily 10 CFR 60) and by issuing appropriate licenses. Under current law, disposal of transuranic wastes from national defense activities is not regulated by the NRC; therefore, the DOE will implement our requirements for disposal of these transuranic wastes.

The containment requirements in Subpart B will be applied through design specifications, and the implementing agencies will have to evaluate long-term projections of the disposal system performance. As a result, a vital part of implementation will be the use of adequate models, including the probabilities of unplanned events, to relate appropriate site and engineering data to projected performance. The NRC has made substantial progress in developing such analytical models to predict long-term performance of actual geologic repositories. These models are quite detailed, and they are capable of evaluating how important any uncertainties in specific types of data are to the overall projections of repository performance. Thus, they can provide information about any needs for obtaining better data to determine if repositories meet the containment requirements of these standards.

At our request, the National Academy of Sciences studied the difficulties in verifying compliance with long-term environmental protection requirements for geologic disposal (NAS 79). Our NAS panel developed an approach that specifies the types of information needed and outlines appropriate methods for obtaining this data at prospective sites. Based on this NAS study, the NRC models, our own analytical efforts, and the confidence that should be provided by our assurance requirements, we have concluded that our containment requirements can be effectively implemented.

Chapter 3

ISSUES IN SETTING THE DISPOSAL STANDARDS

Our standards for disposal of high-level and transuranic wastes are intended to provide long-term protection over the very long periods that these materials present a possible hazard to man. This approach introduces questions not ordinarily considered in regulatory decisions having only short-term impacts. For disposal of high-level wastes, most of the potential harm would occur far into the future. This chapter, therefore, describes how we addressed each of the following questions:

1. How should we treat risks to future generations?
2. How should we assess the capability of disposal systems to reduce long-term risks?
3. How should we consider the uncertainties in predicting the future?
4. How should we express the standards to best reflect the environmental protection objectives we desire?
5. How should we select the period of time over which we should regulate?

3.1 RISKS TO FUTURE GENERATIONS

The National Environmental Policy Act (NEPA) requires that we consider risks to future generations. Since disposal of high-level and transuranic radioactive wastes create some risks for present and future generations, regulatory actions must attempt to reduce those risks to an acceptable level.

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Some might argue that no risks to future generations from disposal of these wastes should be allowed, since these generations receive no direct benefits from present activities and since they cannot take part in decisions to create such risks. Others would hold that the industrial, medical, scientific, and military activities that produce the wastes may contribute to the knowledge and security of future generations. Moreover, some of these activities may be alternatives to activities that might result in worse long-term pollution and in depletion of resources. These indirect benefits may justify some risks to future generations from the long-lived radioactive wastes generated by these activities.

We have not tried to resolve this question of intergenerational equity by attempting to make risk versus benefit judgments. We believe that the risks to future generations should be small--at the very least, we should not pass on to future generations any radiation risks greater than risks we would be willing to assume ourselves. We do not know of disposal technologies foreseeable within this century that can eliminate all risks to future generations from disposal of these wastes. However, our analysis of the risks associated with undisturbed uranium ore bodies has reinforced our decision about the reasonableness of the residual risks permitted under our proposed disposal standards. This analysis indicates that leaving equivalent amounts of uranium ore unmined presents at least as great a risk to future generations as disposal of the wastes covered by these standards. Thus, there would appear to be no increase in future risks caused by disposal of these wastes.

We are not sure that this analysis provides an adequate means of resolving the question of intergenerational risk. It has, however, helped to influence our decision of what is an acceptable level of residual risk given our current scientific, technological, and fiscal capabilities. The following discussion provides more details on the perspectives we used to evaluate risks to future generations.

3.1.1. Perspectives on Long-Term Risks

People have always been exposed to radiation. Life has evolved in a natural background radiation field that gives most humans doses on the order of 100 millirem per year. Man has added more radiation--from medical, industrial, and national defense activities--to this natural background. We believe our standards should limit the risks from high-level and transuranic wastes after disposal to a small fraction of today's radiation risks. As a basis for comparison, we present estimates of the risks from four radiation sources. Two of these sources, natural background radiation and uranium ore bodies, are relatively constant, and the risks will continue far into the future. The risks from the other two sources, generation of nuclear power and nuclear weapons fallout, are largely short-term and will decrease with time. The estimates of risks from natural background radiation, generation of nuclear power, and nuclear weapons fallout are much higher than those we estimate from high-level wastes after disposal. The estimates of risks from uranium ore bodies vary over a large range. Our estimates of the risks from the disposal of high-level wastes are slightly above the lower bound of this range and are substantially less than the higher part of the range.

3.1.2. Risks Associated with Natural Background Radiation

Humans are exposed to natural background radiation from cosmic rays, from naturally occurring radionuclides in the earth, and from naturally occurring radionuclides in the body, primarily potassium-40. Cosmic radiation originates primarily in galactic and solar processes. Naturally occurring radionuclides in the earth's crust comprise chiefly members of the uranium-238 series, members of the thorium-232 series, and potassium-40. There are approximately 2.7 grams of uranium-238, 9.6 grams of thorium-232, and 20,900 grams of potassium per metric ton of rock in the earth's crust (FO 71). Rock in the earth's crust contains about 1.4×10^{-5} curies of alpha activity per metric ton and about 2.7×10^{-5} curies of beta activity.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has estimated that the average annual radiation dose from external exposure to natural sources in "normal" areas of the world includes 28 millirads of cosmic radiation and 32 millirads of terrestrial radiation (UN 77). The UNSCEAR committee stated that the dose from external and internal radiation was 92 millirads per year to red marrow, 78 to gonads, and 110 to lungs. The corresponding dose equivalent rates, with a quality factor of 10 for the alpha and neutron components, are 109, 86, and 425 millirem per year (mrem/yr), respectively. The difference among organs is due to differing radionuclide contents in the organs.

People receive from about 50 to about 195 mrem/yr natural background radiation dose equivalent from cosmic, terrestrial, and internal radiation. The highest dose equivalents received in large urban areas are about 130 mrem/yr in Denver, Colorado, and about 115 mrem/yr in Albuquerque, New Mexico. The highest average for a state is about 115 mrem/yr in Colorado. Table 3-1 gives the distribution of the dose received by the population. It shows that about 60 percent of the United States population receives from 65 to 90 mrem/yr; 20 percent more than 90 mrem/yr; and 5 percent more than 105 mrem/yr. Natural background radiation levels in the United States vary by a factor of three.

Information on the variability of the dose equivalent received by people in the United States has been published by Oakley (OA 72) and revised by Bogen (BO 80). Cosmic radiation dose equivalent in the United States varies from 29 mrem/yr at sea level to about 125 mrem/yr at 3200 meters (10,500 feet), the altitude of Leadville, Colorado (NCRP 75). The terrestrial component dose equivalent from radionuclides in the earth can be characterized as low (average of 23 mrem/yr) for the Atlantic and Gulf coastal plain, moderate (average of 46 mrem/yr) for most of the rest of the United States, and high (average of 90 mrem/yr) for a small region in the Colorado Front Range.

Table 3-1

Distribution of Natural Radiation Dose Equivalents

(Terrestrial Plus Cosmic Plus Internal)

Dose equivalent* (mrem/yr)	Percentage of U.S. Population receiving more than stated dose
50	100
65	80
75	50
90	20
105	5
120	1

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*Dose equivalent includes 25 millirem per year from internal radiation. Values have been rounded to the nearest 5 mrem/yr.

We estimate that an excess of about 200 fatal cancers per million person-rem can be expected (NAS 72). This means that an increase of 1 mrem/yr in natural background radiation (about 1 percent) to everyone in the present U.S. population would result in about 40 excess fatal cancers per year. A 1 mrem/yr increase in radiation exposure to 5 million people (a population that might be exposed to releases from a large high-level waste repository) would result in about one additional fatal cancer per year.

Risks associated with natural background radiation are similar to those from radioactive wastes; both produce the same kinds of health effects and both persist for long periods of time. The risk from natural background radiation is much larger than that projected for releases from a high-level waste repository. However, in general, the variability of this risk does not seem to greatly influence the choice of people in selecting a place to live.

3.1.3 Risks from Uranium Ore Bodies

A comparison of the risks from a high-level waste repository with those from an undisturbed uranium ore body offers another useful perspective. In making our assessment (WI 80), we consider that uranium dissolved by the groundwater eventually reaches a stream. As the uranium moves along the aquifer, radium-226 and other daughters are formed. We estimated the risk from a model generic ore body containing 620,000 tons of uranium oxide, the amount that would have to be mined to produce the high-level wastes contained in our model repository. For this estimate we used the same generic environmental model (SMJ 82) that we used for assessing the risk from high-level radioactive wastes in mined geological repositories (SMC 82).

The risks from uranium ore bodies cover a wide range, depending on the ability of uranium and its decay products (particularly radium-226) to leave the ore body and reach people. To estimate a minimum impact, we selected a uranium concentration in groundwater at the low end of the reported range (FI 55). For this assumption, we calculate an occurrence of two excess fatal cancers per 100 years for the model generic ore body. Based on pre-operational data for three actual uranium mines, we calculate the impact of releases of radionuclides to groundwater to cause between 100 to about 1000 excess cancers per year. These estimates from actual ore bodies may be high, because the reported concentrations in the groundwater include some measurements from the oxidizing uranium-rich groundwater. Our estimate of the risks from the wastes after disposal is, therefore, similar to the lowest estimates of risk from the unmined ore bodies.

3.1.4 Risks from Nuclear Power Generation

Ellett and Richardson (EL 77) estimated that exposure to the radiation incident to the generation of 1 gigawatt-year of electrical energy could result in an average of about 1.2 fatal cancers* in the first 100 years.

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*The estimated number of fatal cancers represents a probability of incidence in the entire exposed population.

More recent information reduces this estimate to 0.8 fatal cancers. Operation of the 50 gigawatts of nuclear power generation available in 1977 (ADL 79) at 60 percent of capacity could cause about 24 fatal cancers per year. To the extent that radionuclides such as carbon-14, thorium-230, and radium-226 and its daughters persist beyond 100 years, this estimate may be low.

Since they are limited in time, the risks from generating nuclear electric power are not directly comparable to risks that would be associated with disposal of high-level radioactive wastes, but they do offer a perspective. Our estimate of the risk from the wastes for 10,000 years after disposal is less than the current population risks from generating the electricity.

3.1.5 Risks from Nuclear Weapons Fallout

Fallout from atmospheric testing of nuclear weapons has added to the radioactivity of air, water, food, and residual radionuclides (primarily tritium, strontium-90, cesium-137, carbon-14, and plutonium) and is a source of continual radiation exposure. UNSCEAR has estimated the dose commitments to various organs of an average individual in the northern temperate zone from nuclear weapons testing through 1975 (UN 77). The UNSCEAR values are shown in Table 3-2. When converted to millirems, the dose commitments are 150 millirems to gonads, 260 to bone marrow, 300 to bone linings, and 270 to lung. Almost all the dose commitment is due to relatively short-lived (30 years or less) nuclides, because doses for carbon-14 were calculated only to the year 2000.

Table 3-2

Dose Commitments from Fallout (UN 77)

(Northern Temperate Zone)

	millirad			
	Gonads	Bone Marrow	Bone Lining	Lung
External				
Short-lived	48	48	48	48
^{137}Cs	62	62	62	62
Internal				
^{14}C (a)	7	32	29	9
^{90}Sr		84	120	
^{106}Ru				41
^{137}Cs	27	27	27	27
^{144}Ce				65
^{239}Pu			1	1
TOTAL (b)	150	260	290	260

(a) Dose accumulated up to the year 2000
(b) Including nuclides not listed

We estimate the number of projected fatal cancers in the United States population from fallout by multiplying the average dose commitments in Table 3-2 by 200 million and by the appropriate risk factors. We have assumed that the soft tissue dose is equal to the gonadal dose and have reduced the whole body risk factor of 200 per million person-rem to 110, to avoid counting the fatal cancers from the listed organs twice. The expected harm from nuclear weapons testing in the United States is then about 3300 fatal cancers from soft tissue irradiation, 2080 from bone marrow irradiation, 600 from bone lining irradiation, and 2160 from lung irradiation, for a total of 8140 fatal cancers over the life of the nuclides involved. If this number is averaged over the half-lives of cesium-137 and strontium-90, the largest contributors to the dose commitment, the result is an average of about 190 fatal cancers per year over about 43 years.

The risks from nuclear weapons fallout are primarily near-term risks and are relatively uniformly distributed over the northern hemisphere. Therefore, they are not directly comparable to the risks from the disposal of waste. The present annual risk from fallout is about 2000 times greater than the projected future annual risk from the wastes after disposal.

3.2 ASSESSMENT AND REDUCTION OF RISKS

An important element in the development of environmental standards is an assessment of technology to control risks. In this discussion, we deal with the quantitative assessment of risks, including the effect of uncertainty, and consider some methods suggested for the disposal of high-level and transuranic radioactive wastes.

3.2.1 Assessment of Risks from Waste Disposal

No high-level or transuranic radioactive wastes have ever been disposed of permanently. Because there is no background of experience that can be used as a basis for analysis, we must rely on modeling procedures for an assessment of risk. To model the characteristics and performance of a disposal system, mathematical equations must be developed that predict potential releases of waste and describe their subsequent transport through the environment. These models predict the consequences of releases over long periods of time. The models can be no better than our understanding of all the processes involved and, in fact, are often simplified to facilitate the complex computations.

The mathematical equations describing the behavior of the system and the movement of radionuclides through the environment to man are designed to be general, and they require appropriate numerical data to produce useful results. Therefore, there are uncertainties both in how well the models describe the actual physical and chemical processes that may occur and also in how good the numerical input data are in terms of producing realistic results.

When attempting to model the behavior of a generic system, we must select numbers descriptive of system characteristics. It is customary to make several model assessments, using several different sets of values for the characteristics we consider important. This practice, which is generally called sensitivity analysis, gives us information on the extent to which each system characteristic influences the overall estimate of risks.

3.2.2 Reduction of Risks by Disposal Technology

Although several methods of isolating high-level and transuranic wastes are being developed, we have chosen to assess disposal in mined geologic repositories. We believe that this is the only method for which sufficient information is available to provide the basis for judgments needed to develop disposal standards. Any other method for disposal of high-level and transuranic wastes must result in risks no greater than those we have judged would result from disposal in carefully selected and well-engineered geologic repositories.

As part of the development of these proposed standards, EPA asked the MITRE Corporation (AL 79a) to review the scientific and developmental status of alternative disposal concepts. The Interagency Review Group on Nuclear Waste Management, created by the President, and the Department of Energy have also examined alternative disposal technologies (IRG 79), (DOE 80). The Ford Foundation (NU 77) and the American Physical Society (APS 78) have previously reviewed high-level waste disposal concepts, and several other groups, including an Ad Hoc Panel of Earth Scientists commissioned by EPA (EPA 78a), have analyzed aspects of the status of basic science and technology relevant to deep geologic disposal. The following paragraphs describe the status of waste disposal concepts, based on information that is currently available.

Emplacement in Deep Mined Repositories

Radioactive wastes could be placed in underground repositories built with conventional mining techniques. The primary natural barriers to migration of the radionuclides would be the emplacement medium and the surrounding geologic and hydrologic environment. Engineered barriers would include a stable and insoluble waste form, corrosion-resistant containers, and absorbent packing materials. Removal of the material from the immediate proximity of people and other living things would reduce the possibility of accidents during the several-hundred-year period during which fission products dominate the radioactivity. Careful attention to site selection and deep emplacement would make catastrophic release of the waste by severe surface disturbances extremely unlikely.

Our assessments indicate that exploration for resources, in which holes would be drilled into the repository, would be the most common mode of inadvertent release of radionuclides to the biosphere. Drilling could release radionuclides to both the land surface and groundwater. While groundwater would be a pathway by which radionuclides from the waste can enter the biosphere, it would also be a protective barrier. Groundwater velocities are slow enough, in general, that many of the radionuclides in the waste would decay before reaching the surface. Furthermore, adsorption of many radionuclides by the media through which the flow occurs can slow their movement even more and can provide considerable added protection against exposure to radionuclides with moderately long half-lives.

Other Methods of Deep Continental Disposal

Rock Melt. Fresh high-level waste might be emplaced into continental rock formations. The heat generated by the radioactivity of the waste would melt the surrounding rock. When the rock cooled, the wastes would be incorporated in a rock mass that would be impermeable and in good chemical equilibrium with its environment.

Rock melting disposal methods may offer the same protection against catastrophic releases by natural forces and human intrusion as deep-mined geologic repositories. There would, however, be considerable volatilization of radionuclides during the melting period, after which retention of the radionuclides would depend on the extent that they were bonded to the rock during melting. There has been no evaluation of the extent to which radionuclides would be immobilized in this disposal concept, and, therefore, we cannot make an assessment of risk.

Deep Holes. Containers of waste could be placed in the bottoms of holes drilled as deep as 50,000 feet. At such depths, human intrusion would be unlikely. The emplacement of wastes to this depth is not feasible now. Present drilling methods are believed to be capable of drilling a hole 20 centimeters (about 8 inches) in diameter to a depth of about 11,000 meters (35,000 feet) or a hole 31 centimeters (about 12-inch) to a depth of 9.1 kilometers (about 30,000 feet). The ability to seal such a hole has not yet been demonstrated.

Risks from disposal in deep holes would depend on the ability of the rocks around the hole to dissipate the heat and on the absence of groundwater movement in any specific location. Information for such risk assessment is not now available.

Emplacement in Deep Ocean Sediments

Containers of waste or spent fuel could be placed tens of meters or more below the ocean floor in stable regions where the sediments are thick and uniform. The wastes would be far from human activity, and the sediments would be expected to prevent the waste nuclides from reaching the ocean water.

Lack of knowledge of the stability and adsorptive properties of the sediment barrier when wastes are emplaced in it makes it impossible to assess the risks of this method of disposal. Disposal in the ocean is prohibited under United States law by the Marine Protection, Research and Sanctuaries Act of 1972. Legislative action would be required before seabed disposal could be implemented.

Extraterrestrial Disposal

High-level and transuranic radioactive wastes could be launched into space. This method of disposal would potentially eliminate future risk to living things. A solar orbit appears to be the most technically and economically achievable option and would provide long-term isolation. This method would not provide for injection of all the waste into space, because costs would be too high. Present concepts would require chemical separation of the wastes and would send only the long-lived radionuclides into space .

Disposal in space would permanently isolate radioactive nuclides from humans. However, methods for assuring the protection of public health in the event of launch failures have not yet been developed, and separation of wastes introduces added risks. The overall costs of this method of disposal are high.

Transmutation of Waste Radionuclides

Radionuclides in waste could be transformed to less hazardous nuclides by irradiation in nuclear reactors or in particle accelerators. Long-lived and highly radiotoxic actinide radionuclides, including neptunium-237, plutonium-239 and -240, and americium-241 and -243, are the most important candidates for transmutation. However, other long-lived nuclides, such as iodine-129 and technetium-99, have also been considered. Materials to be transmuted would have to be chemically separated from the irradiated fuel. High-efficiency actinide separation has not yet been developed.

Transmutation of nuclides would eliminate any possibility that they would ever affect people. However, other risks of transmutation have not been fully evaluated and may be high. Separation and recycling of the actinides and other radionuclides could increase occupational, transportation, and routine release risks.

3.3 DEALING WITH UNCERTAINTIES

In considering the possible harm that might be incurred in the future by people as a result of releases from a disposal system, we must allow for uncertainties in our expectations of the future. In our development of this proposed action, we did this in two ways: by using conservative values in our assessments and by including the qualitative assurance requirements in our proposed standards. In the following paragraphs, we will discuss the issues of uncertainty in disposal system performance and of future human behavior.

3.3.1 Technical Uncertainties

Disposal systems limit potential harm to people from the disposal of high-level and transuranic radioactive wastes by placing barriers between the wastes and the human environment. Judgments of the acceptability of the system depend on estimates of the effectiveness of these barriers. We can make such estimates by considering the performance expected from each barrier, using conservative values, and combining these into an assessment of the performance of the entire system. We allowed for uncertainties in these estimates by selecting values for the effectiveness of each barrier that we are confident are well within the capabilities of engineering and site characterization. The actual effectiveness of each barrier will probably be considerably better than our selected value. The entire system should perform much better than our assessment of its performance, which we obtain by combining our values for the effectiveness of all the barriers.

We also allowed for uncertainty qualitatively by providing for redundant independent barriers. Each barrier would function whether or not other barriers perform in the manner we expect. We believe such redundancy and independence is particularly appropriate for a system that must operate over long periods of time without human control or intervention. Accordingly, we have adopted both the conservative system analysis, which we used to select limits on the quantities of radionuclides projected to be released into the accessible environment, and the qualitative concept of redundant independent barriers included in our assurance requirements.

We could also have required that the disposal system meet our containment requirements even if some of their barriers are assumed to fail. Such a requirement might be stated as: (1) meet the numerical requirements even if any one of the barriers fails, or (2) meet the requirements if only one of the barriers works. A repository built to comply with such requirements probably would be much more expensive than other designs we have studied, and much of the necessary technology does not appear to exist yet. Although some additional protection might be provided by such an approach, we do not believe this would justify the extra costs, difficult implementation, and long delays that would result.

We must also consider the possibility of presently unknown processes and phenomena that could produce much greater risks than we project from the system. Development of technical and scientific knowledge has often revealed such unexpected processes or phenomena. Our knowledge of ionizing radiation itself is less than a century old. In geology, the theory of tectonic plate movement is quite recent. Therefore, to allow for such possible major technical uncertainties, we believe that we have an obligation to leave future generations the option of removing the wastes from a disposal system found to be excessively hazardous. Accordingly, we are proposing an assurance requirement that requires disposal systems to be designed so that recovery of most of the wastes is not precluded for a reasonable period after disposal.

Some disposal methods, such as deep-hole disposal and rock-melting concepts, may not be able to comply with this assurance requirement. If we did not include this provision, it might be possible to develop disposal methods that would have smaller projected risks than those we project for mined geologic repositories. However, if we were to dispose of wastes in a way that could not be reversed, then future generations would not have the option to take advantage of new information or better technologies. We believe that mined geologic disposal methods, from which wastes can be recovered, can keep the projected risks to future generations small, and we judge that any additional protection is less important than retaining future options to alter the disposal method, if necessary.

3.3.2 Uncertainties in Human Behavior

Human behavior in the future may affect the risks from disposal facilities in two ways. First, human actions may change the ability of the system to isolate the wastes (for example, if a person drills through a geologic repository while exploring for some mineral resource, he may provide a pathway through which radionuclides can reach people). Second, human actions may affect the likelihood of human exposure to radionuclides that have escaped from isolation (for example, exposure to radionuclides in contaminated groundwater occurs only as a result of using the water).

Institutional Controls

Institutional controls are intended to assure the integrity of a waste isolation repository and to eliminate the possibility of human damage to the isolation capacity. The pertinent issue regarding institutional controls is how long we should rely on them in our planning and design of disposal facilities. Different attitudes toward institutional controls can lead to very different strategies for protecting the environment. This issue was discussed extensively during the development and review of the Federal radiation protection guidance for disposal of all types of radioactive wastes that we proposed on November 15, 1978. Institutional control was defined as "activities, devices, and combinations thereof which involve the performance of functions by human beings to limit contact between the waste and the humans or the environment." The proposed criteria stated ". . . Controls which are based on institutional functions should not be relied upon for longer than 100 years . . .".

Public comments with specific recommendations about how long we should rely on institutional controls were divided approximately evenly among four positions:

1. That institutional controls should be relied upon for only about 20 to 30 years.
2. That the 100-year period was about right.
3. That the 100-year period should be extended to 500 to 1000 years, or even longer.
4. That we should limit reliance on controls, but let the regulatory agencies select the appropriate time period.

On balance, a few more commenters felt that the 100-year period was too short compared to those who felt it was too long. Several other comments made a distinction between "active" controls, such as restricting access to disposal sites, and "passive" controls, such as warning future generations about what we have done by creating extensive records and markers.

In the proposed assurance requirements that are part of these standards, we have decided to limit reliance on "active" controls--such as guarding a disposal site, performing maintenance operations, or controlling or cleaning up any releases from a site--to a "reasonable" period of time after disposal, which we believe should be no more than a few hundred years. However, because the Federal Government is committed to retaining control over these disposal sites in perpetuity, we expect that "passive" institutional measures should substantially reduce the chance of inadvertent human intrusion well beyond this period. Such passive controls will include permanent markers placed at a disposal site, public records or archives, Federal ownership or control of land use, and other methods of preserving knowledge about the disposal system. These passive controls should not be assumed to prevent all possibilities of inadvertent intrusion, because there is always a chance that the controls will be overlooked or misunderstood. However, such measures should be effective in deterring systematic or persistent exploitation of a disposal site.

As one alternative to this proposal, we could have assumed that institutional controls such as those we now use would be effective for a very long time (thousands of years). Inadvertant human intrusion would not be a concern, and few areas would have to be avoided because of resource potential. This would permit use of monitored, engineered storage systems--carefully designed to reduce the chances of accidental releases--which would have a number of advantages over disposal systems. In particular, failures of the waste containment could be quickly detected and corrected before significant contamination of the accessible environment occurred.

On the other hand, we could have assumed that society could lose all knowledge of the disposal system and the dangers of its contents in a relatively short period of time. Thus, not only could people intrude into the system, they might not respond to any unusual conditions they encountered and might continue to spread the wastes throughout the environment for a long time. In this case, the first priority for a disposal method would be to reduce the chance of inadvertant intrusion as much as possible, even if this resulted in higher risks from other events. This would strongly affect the relative attractiveness of various disposal methods. Techniques such as deep-hole placement, which removed the wastes far from man's typical activities, would be favored. We also might have to delete our assurance requirement that the wastes be recoverable, to avoid ruling out many of these disposal techniques.

When there are no active institutional controls, the likelihood of inadvertant human intrusion into the disposal area may be reduced if the existence of the disposal site is known. The waste disposal system can provide such information in the form of archival records and permanent markers at the site. In the public workshops leading up to our November 15, 1978, proposal of Federal radiation protection guidance for radioactive waste disposal, there was general acceptance of the concept of passive communication of the disposal system (EPA 78b). Over long periods of time, any particular marker or record may be destroyed or lost, but wide distribution of duplicate records would greatly reduce the likelihood of all knowledge of the disposal location being lost. Accordingly, we have included an assurance requirement for markers and records.

Resource Potential

We must consider the possibility of human activities that would degrade the isolation capability of a waste disposal system in the absence of active institutional controls or of knowledge of the disposal system's existence. Human intrusion is more likely if the disposal site can be expected to yield valuable mineral, energy, or other resources. Locations that are now known to contain actual or potential resources, such as coal or oil shale, must be avoided.

We must be cautious in our judgments as to what would be attractive to future prospectors, because we cannot predict what materials will be valuable to people in the future. A few centuries ago oil, uranium ores, and aluminum ores were not significant resources. In our assurance requirements, therefore, we state that wastes should not be placed in an area where there is a reasonable expectation of future mining or exploration. To allow for our uncertainty about what materials may be considered valuable in the future, we extend this requirement to sites containing a substantial concentration of any material that is not widely available.

3.4 CHOICE OF FORMAT FOR DISPOSAL STANDARD

In developing the proposed standards, we considered a number of possible ways to limit risks to individuals or population groups. We also considered a number of possible time periods over which we should regulate. This section and the following one evaluate these alternative approaches to the disposal standards.

Alternative 1: Standards expressed in numbers of health effects projected over some period of time. This form most directly addresses the population risks and would be preferred, all other things being equal. However, regulations in this form require assumptions on the exact relationship between dose and health effects and would also require knowledge of future population and demography at a site, an obvious impossibility. We therefore rejected Alternative 1.

Alternative 2: Standards expressed in terms of population dose equivalents (person-rems) over some period of time. This form requires no assumptions as to the nature of the dose response (health effects per person-rem) but is otherwise similar to Alternative 1. It would require the same knowledge of future population and demography as Alternative 1, and therefore we rejected it also.

Alternative 3: Standards expressed in dose-equivalent to individuals over a lifetime. This form would provide an estimate of the total risk to an individual. However, this alternative might not assure adequate protection to the total population, and it appears very difficult to implement. We therefore rejected this alternative.

Alternative 4: Standards expressed in terms of dose equivalent rates (rem per year) to individuals. This form measures risk in terms of annual increments of exposure and is more useful in regulating short-term hazards than for controlling long-lived radionuclides. However, this alternative (or equivalent standards which limit radionuclide concentrations in air or water) is a traditional form of radiation protection standard. Therefore, although we rejected this option, it is further examined in Chapter 4 as one of the major alternatives to our proposed action.

Alternative 5: Standards expressed in terms of total integrated radionuclide releases (curies) to the accessible environment over a long period of time. This choice would serve as a surrogate for Alternatives 1 and 2 in estimating population risk. Standards in this form would be easier to implement, since they only require estimation of the probable quantities of radionuclides leaving the disposal site and their physical transport to a location accessible to man. For these reasons, we selected this form for the standards.

Alternative 6: Standards expressed in terms of radionuclide release rates to the accessible environment (curies per year). Our investigations (SMC 82) showed that radionuclide release rates were less closely related to population risk than total radionuclide releases. We rejected Alternative 6 for this reason.

Alternative 7: Standards expressed in concentration of radionuclides (curies per cubic meter) in environmental media. Concentrations of radionuclides in specific environmental media are less closely related to population risk than total curie releases, and standards in this form could encourage siting where there are large volumes of diluting water. Although this could reduce doses to exposed individuals, the ultimate population dose would be the same. The calculations required for implementation of this standard would be much more difficult, because they would require detailed analysis of environmental pathways. We therefore rejected this alternative, but--as discussed for Alternative 4 above--this overall approach is considered as one of the major alternatives to our proposal in Chapter 4.

3.5 ALTERNATIVE REGULATORY TIME PERIODS

The goal of our disposal standards is to provide protection as long as the wastes present an unacceptable risk. The standards require a reasonable expectation that releases over a specified time will be less than the specified limits. Stating a period for regulation in the standard does not imply that the radioactive wastes will be released after that time; it establishes the period over which the releases must be assessed. We considered several alternative time periods for assessment: 100 years; 1000 years; 10,000 years; 1,000,000 years; and forever. We could also have based our assessment on the risk to any future generation.

Alternative 1: 100 years. The Uranium Fuel Cycle (UFC) regulations (40 CFR 190) are based partially on 100-year projections of risk. In those regulations, we limited the projections to 100 years because of uncertainties in population, demography, and use of the environment. We do not need precise estimates of risk for development of these proposed high-level and transuranic radioactive waste standards, because balancing these risks and costs is not a major basis for the standards. Our risk assessments showed that few health effects are predicted in the first hundred years, mainly because of long groundwater transport times and the low probability of disrupting events in such a short time period. Therefore, an analysis of consequences limited to 100 years after disposal would give an unrealistically low estimate of the total potential impacts. We rejected this alternative for these reasons.

Alternative 2: 1000 years. Some have suggested that most risks occur in the first 1000 years, because strontium-90 and cesium-137 decay in that time. The same considerations that argue against the 100-year period apply to the 1000-year period. Few health effects occur during this period; many nuclides would still be in transit towards the accessible environment; disruptive event probability is still low; and a considerable number of the important nuclides would not have undergone significant radioactive decay. We therefore rejected Alternative 2.

Alternative 3: 1,000,000 years. A period of 1,000,000 years has been advocated on the grounds that the hazard from high-level radioactive wastes is not adequately reduced by radioactive decay until then. However, it would be difficult to make quantitative assessments of the potential environmental impacts of waste disposal over such a long time, and prediction of geological changes over such a long period is not reliable. These reasons make Alternative 3 unacceptable.

Alternative 4: Forever. The arguments against selection of the 1,000,000-year period apply even more strongly to regulation over all time. This option, too, was rejected.

Alternative 5: 10,000 years. We have selected 10,000 years as a regulatory period. In 10,000 years, many of the radionuclides that can pass through groundwater transport paths will have reached surface water and the accessible environment. At 10,000 years, the radiological hazard of the wastes would be substantially reduced through the decay of most of the significant fission products and of many of the actinides. The only remaining nuclides presenting a potentially significant health risk would be technetium-99 and iodine-129 and the actinides plutonium-239 (about 75 percent of the original inventory), plutonium-240, and neptunium-237.

This inventory will decrease fairly rapidly after 10,000 years by decay of plutonium-239 and -240; it will then decrease slowly because of the long half-lives of technetium-99, iodine-129, and neptunium-237. The radionuclide hazard potential at 10,000 years is, therefore, fairly descriptive of the situation for a long time thereafter. Population and demographic conditions 10,000 years from now are unknown and unknowable, but they do not have a controlling effect on setting the standards. Since 10,000 years is a short time geologically, changes in geological conditions are expected to be small. Only massive changes in climate, such as could conceivably be induced by man-made additions to the atmosphere (e.g., the carbon dioxide "greenhouse" effect), could produce large changes in the transport of radionuclides. The adverse effect of these climate changes would be so great that any additional impact of the radioactive wastes would be relatively insignificant.

Alternative 6: A reasonable objective for waste disposal is that no future generation should incur more than a fraction of the risks that would be acceptable to the current generation. We have considered this principle in formulating these standards. However, we also recognize that it could be difficult to implement as stated. The risks to each generation for a long period of time would have to be examined to find out if they were below the appropriate level. Our evaluations of the environmental effects of disposal, described in Chapter 5, indicate that total risks over 10,000 years can be made small. Limiting total risks to this level ensures that no single generation within this period can incur greater risks. These risks do not appear unreasonable even if incurred by only one generation. Therefore, we believe it is simpler and adequate to restrict risks over the total period of 10,000 years rather than provide a limit on risks to a single generation.

Chapter 4

ALTERNATIVES

In developing our proposed environmental standards, we considered a number of alternatives. This chapter examines those alternatives that would involve major changes to our proposed action. Additional alternatives that would affect specific details of the standards are discussed in other chapters of this Draft Environmental Impact Statement: Chapter 3 examines some different approaches we could take to compensate for the uncertainties of the future and also considers different time periods and alternative units for the disposal standard, and Chapter 7 considers alternative dose limits for the waste management standards. Each of our discussions of alternatives indicates why we think our proposed action is preferable to the other options we considered. However, in each case we would like to receive public comments that evaluate whether we made appropriate choices.

Our consideration of alternatives is influenced by the limits on our information. High-level radioactive wastes have never, to our knowledge, been permanently disposed of. Furthermore, since we believe these disposal systems should isolate the wastes for many thousands of years, the relative benefits of different systems can be judged only by predictions of their long-term performance. With this pervasive limitation in mind, the following are the major alternatives to our proposed action.

4.1 ISSUE NO STANDARD

The decision to prepare these standards was an administrative action taken by EPA and was not mandated by law. We were directed to prepare standards as part of President Ford's Nuclear Waste Management Plan on October 27, 1976. President Carter established an Interagency Review Group (IRG) on Waste Management in March 1978 to review existing programs and recommend new policies where necessary; the IRG recommended that EPA set standards for nuclear waste management and disposal activities and accelerate its programs to do so. President Carter approved this recommendation as part of his Program on Radioactive Waste Management announced on February 12, 1980. The NRC best described (NRC 80) the expected goal of these standards:

> ". . . (EPA) standards represent a broad social consensus concerning the amount of radioactive materials and levels of radioactivity in the general environment that are compatible with protection of the health and safety of the public."

Although satisfactory management and disposal of high-level radioactive wastes could be attained by other regulatory means (e.g., NRC licensing requirements), such means would not likely receive broad public acceptance. By promulgating standards, EPA directly focuses on environmental protection requirements without the constraints of many of the complex engineering requirements necessary for consideration in licensing. Also, because of its broad environmental charter, EPA is in the best position to assure broader input into the standards by groups outside nuclear interests--e.g., those charged with protecting groundwater. Thus, not issuing standards is an unacceptable option.

4.2 DELAY ACTION

We could have chosen to delay issuing standards until we developed more information about disposal systems. This delay could allow us to better evaluate how well disposal systems can protect the environment and might lessen the chance of poor judgments of how much protection is necessary and reasonably achievable. We might then be able to develop information on disposal systems other than geologic repositories and to develop quantitative comparisons of the costs and benefits of these alternatives. However, we do not expect enough information to become available during the next decade to allow more comprehensive evaluations.

We choose to propose these standards now, because we believe that environmental standards must be developed to guide the progress of the national waste disposal program. DOE has decided to focus the national program on mined geologic repositories (46 FR 26677), after evaluating alternatives through a comprehensive environmental statement process (DOE 80). The DOE program anticipates identification and characterization of three sites at which to begin exploratory shaft construction in 1983. The overall goal is to provide the first licensed, fully operational repository within the period 1997 to 2006 (NE 81).

Delay in proposing these standards could diminish public confidence in the national waste management program. Loss of confidence might lead to action by more state governments to restrict exploratory and research activities. This could reduce the options available to the Federal government in exploring for repository sites. We believe that proposing standards now will enable the national radioactive waste disposal program to proceed on an orderly schedule. This is consistent with the synopsis of the public comment received by the IRG (IRG 79):

> "Comment from both the industrial sector and the environmental community urged the acceleration of EPA standards particularly to instill confidence that proper protection of the public's health and safety is being provided. They expressed the concern that early standards are essential to permit the waste management program to proceed expeditiously."

In addition, proposing these standards now will reduce the chances of harm from long-term storage of existing wastes in surface facilities. Although such storage offers no significant danger under normal conditions, the wastes are more vulnerable to accidental release. For example, several leaks have occurred from the high-level waste storage tanks at Hanford (ERDA 75). These leaks have not caused any exposures of the general population, nor have they contaminated any areas beyond the site boundary. However, they do represent unplanned releases that could have had serious consequences. We believe that our standards will adequately protect public health and expect that disposal technologies satisfying these standards will be available within the next decade.

4.3 ESTABLISH ONLY QUALITATIVE REQUIREMENTS

The large uncertainties inherent in predicting the performance of disposal systems over thousands of years present an argument for issuing environmental protection requirements that contain only qualitative criteria--such as our proposed assurance requirements. Application of such criteria would be easier than implementing our proposed standards: regulation on the basis of qualitative criteria would not require any projection of releases over time, and the validity of models for predicting those releases would not come into question. Instead, selection and licensing of disposal methods could rely more upon the informed judgments of technical experts (subject to appropriate review) than upon uncertain numerical estimates. Issuing only qualitative requirements would still provide instructions that could effectively reduce the dangers of disposal, and such criteria could be used to compare alternative disposal systems and to select among them. Since such qualitative requirements--by themselves--would not be appropriate generally applicable environmental standards, we would issue them under our Federal radiation protection guidance authority.

Our quantitative environmental protection requirements provide at least two important benefits, however:

1. By selecting the form of these protection requirements as numerical release limits over a particular time, we identify those overall objectives that should be considered in disposal system design. (One example: setting stringent release limits rather than individual exposure limits encourages very good containment rather than suggesting dilution as part of a disposal strategy. Another example: a disposal system designed to limit releases for 1000 years could rely primarily on engineered barriers, whereas a system

designed to retain wastes for 10,000 years also would require both good geological and hydrological characteristics at the disposal site.)

2. Setting quantitative standards requires a full assessment of system performance to assure that these standards will not be exceeded--and this requirement for a comprehensive examination of the potential harm can provide confidence that disposal systems will behave as expected and will not create more than a small risk to public health.

4.4 DELETE OR DEEMPHASIZE THE QUALITATIVE ASSURANCE REQUIREMENTS

In contrast to the previous alternative, this approach would increase the reliance on our quantitative containment requirements. It would provide greater flexibility for selection and design of disposal systems--since the emphasis of our action would be on achieving specific environmental protection objectives without restrictions on how those objectives should be met. (For example: system designers might choose to use a single, extremely effective barrier, or they might decide to depend on indefinite control of the site to meet our requirements.) As part of this alternative approach, the NRC could be expected to provide any appropriate procedural, site selection, or system design requirements that might be needed beyond our quantitative standards.

There are two variations of this approach that we considered:

- to simply delete the qualitative assurance requirements, leaving only the containment requirements and the procedural requirements needed to assess compliance, or
- to issue the assurance requirements as Federal radiation protection guidance, rather than as part of the generally applicable environmental standards.

The second variation would make the qualitative criteria less binding since--as executive directives rather than formal rules--they could be waived if specific situations warranted. Such waivers would be considered in accordance with the procedures established under Executive Order 12088.

The concept of allowing maximum flexibility to achieve specific environmental protection goals (saying "what to do", not "how to do it") can be very effective in many situations. However, we do not believe we should rely upon it in this case because of the unusually large uncertainties inherent in designing disposal systems to isolate wastes for at least 10,000 years. Instead, we think the cautious steps called for by our assurance requirements should be an integral part of our standards in order to develop appropriate confidence that our containment requirements will be complied with.

Although the specific design requirements that will be developed by the NRC could meet the objectives of our assurance requirements, we believe that our standards should be expected to establish the complete framework of quantitative and qualitative environmental protection requirements that are needed. Furthermore, one category of wastes covered by these standards--transuranic wastes from national defense activities--is not subject to NRC regulation.

4.5 SELECT CONTAINMENT REQUIREMENTS ON A DIFFERENT BASIS

We have proposed containment requirements that we believe are achievable by well chosen and carefully designed geologic repositories and that would limit harm to future generations to low levels. We could have used different bases for selecting these release limits. In the following paragraphs we examine some alternative approaches for picking the containment requirements.

-- Develop Projected Release Limits Considering Different Disposal Methods

An analysis of the potential performance of several disposal methods besides mined geologic repositories might allow us to set more restrictive limits. These alternative disposal methods are described in Chapter 3. However, we cannot do the necessary analyses now or in the near future, because the needed information for any other disposal method will not be available for a long time. Therefore, since this alternative would significantly delay these standards, it is essentially the same as the "Delay Action" alternative discussed previously.

-- Limit Risks to Future Generations from the Entire Nuclear Fuel Cycle, including Waste Disposal, to Those That Would Exist from the Original Unmined Uranium Ore

The Natural Resources Defense Council (NRDC) (CO 79) has proposed this criterion for radioactive waste disposal. The underlying principle is that nuclear power should cause no increase in risk to future generations. This alternative would involve consideration of all long-lived wastes (not limited to high-level wastes) and effluents associated with the nuclear fuel cycle. It would also raise the question of comparing risks to future generations from nuclear power with those from any other sources of energy from which some residual risk is passed on to future generations. We believe this is beyond the scope of this standards-setting effort and, therefore, have not directly used this criterion in developing these standards.

-- Limit Risks to Future Generations from High-Level Waste Disposal to Those That Would Exist from the Original Unmined Uranium Ore

This alternative is related to the criterion proposed by the NRDC. However, it is less restrictive since it considers only one part of the future risks from the nuclear fuel cycle. The risks from ore bodies vary over a wide range, depending on local conditions such as solubility of uranium in the local water, hydrological factors, and transport of radon through environmental media. There are also many uncertainties in our ability to assess the risks from a particular ore body, including uncertainties in sampling, in measuring the characteristics of environmental pathways, and in demography. We estimated risks from unmined uranium ore ranging from somewhat less than, to one-thousand times greater than, the risks from disposal of the high-level wastes derived from the ore (WI 80).

If we used this concept to select containment requirements, the large uncertainties would make it difficult to decide where to set the limits. We believe the risks from disposal in systems complying with our proposed release limits will be no greater than the risks from most equivalent amounts of unmined uranium ore, and most likely will be less. Therefore, we did not choose this alternative, since it would not provide more protection and would be a very uncertain basis for regulation.

4.6 SET HIGHER OR LOWER RELEASE LIMITS

For the release limits we have proposed as our containment requirements, the residual risks projected by our generalized environmental pathway models would be less than 1,000 premature deaths from cancer over the 10,000 year period, an average of one premature death every 10 years. To judge the effects on disposal costs of changing this level of protection, we also compared release limits corresponding to residual risk values of: 100, 1000, 5000, and 10,000 premature deaths over the 10,000 year period. We chose this range of stringency levels because it appears to represent the range of performance that may be expected of mined geologic repositories.

To do this assessment, we evaluated the long-term performance of generic models of geologic repositories in three different geologic media: bedded salt, granite, and basalt. We did the assessment in two steps. First, we used the performance projections decribed in Chapter 5 to assess the quality of the engineering controls that would be needed in each of the three model repositories to meet each of the four different levels of protection. Second, we tried to allow for the possible effect of alternative stringency levels on site selection. This is particularly relevant because our analyses indicate that the most important part of the protection offered by a mined geologic repository comes from the hydrological and geochemical characteristics of the site itself. These calculations are further described in Chapter 9 and in our Draft Regulatory Impact Analysis (EPA 82).

The results of these assessments of disposal costs and alternative stringency levels indicate that the costs are not very sensitive to different levels of protection, particularly for the geologic media (bedded salt and granite) that appear to be better at reducing long-term risks. The differences in costs for different levels are much smaller than the overall uncertainties in waste management costs. For example, consider the increased costs of complying with the release limits we have proposed, rather than release limits 10 times less stringent. The potential increase ranges from zero to 50 million (1981) dollars per year. For comparison, the total costs of high-level waste management and disposal (independent of our action) have been estimated as between

700 million and almost 1.5 billion (1981) dollars per year. Electrical utility revenues were about 100 billion dollars in 1980. The possible impacts of this potential increase in disposal costs are estimated to be less than a 0.2-percent increase in the costs of nuclear power and less than a 0.06-percent increase in average electricity rates (EPA 82).

These analyses, while indicating that disposal costs appear to be relatively insensitive to differences in the level of protection, do not provide a way to determine the acceptability of the residual risks from a societal perspective, nor do they indicate a level of protection that is preferable from a balancing of costs and benefits. One possible approach to balancing costs and benefits would be to judge the cost per life saved by different levels of protection, perhaps taking into account some method of discounting costs and benefits. However, our calculations of residual risks are not reliable as absolute values. Thus, we have no meaningful way to calculate an absolute value of the cost per life saved by different levels of protection.

In the absence of the ability to make meaningful cost and benefit comparisons, we have used other tests of economic feasibility and acceptability of risk to judge the appropriateness of the level of protection we have proposed. As discussed above, setting the release limits at the level we chose--as opposed to a level 10 times less or 10 times more stringent--appears to cause only very minor effects on the costs of high-level waste disposal. This is why we did not choose higher (less protective) release limits.

To judge the acceptability of the remaining long-term risk, we considered the risks that would otherwise be caused if the uranium ore used to produce the wastes had not been mined. As described in the previous section, the magnitude of the risks from these unmined ore bodies is very uncertain due, in part, to the wide variety of settings in which uranium ore is found--many of which are closer to the surface than a geologic repository would be. Using the same generalized environmental pathway models that were used to assess the risks from our models of geologic repositories, the risks from a comparable amount of unmined uranium ore are estimated to range from a few hundred to more than 1 million health effects over 10,000 years. The lower end of this range is roughly equal to the residual risk associated with our proposed release limits. Thus, the upper limit of the risk that our standards would allow from the disposal of high-level wastes appears to pose a threat very close to the minimal risk posed by nature had the uranium ore never been mined and the high-level wastes never been generated. This is why we did not choose lower (more protective) release limits.

4.7 SET DISPOSAL STANDARDS IN TERMS OF LIMITS ON MAXIMUM INDIVIDUAL EXPOSURE

Individual exposure limits, or equivalent standards that limit radionuclide concentrations in air or water, are a traditional form of radiation protection standard. Particularly when the limits are comparable to or less than natural background levels, they may be more effective than our proposed standards at communicating how small the chance of harm from disposal of these wastes should be. However, we chose not to use individual exposure limits in Subpart B because of two unique aspects of the situation regarding our disposal standards:

First, these disposal systems have to protect the environment from these highly concentrated radioactive wastes for much longer than institutional controls can be guaranteed to be effective. Any individual exposure limit we set could apply only at some distance from a repository, or it would have to ignore the risks from unplanned events such as inadvertent intrusion--because individuals who fail to understand passive warnings and penetrate directly into or close to a disposal system (through exploratory drilling for water or mineral resources, for example) could receive very large exposures. These exposures would probably exceed any reasonable individual exposure standard.

Second, the disposal standards have to be applied through analytical performance projections--implementing such standards through environmental monitoring and potential remedial actions over thousands of years is not a credible approach. When we compared the analyses needed for compliance with exposure limits to the analyses needed for compliance with release limits, we found that our proposed disposal standards would be much easier to implement than exposure limits. The NRC, which is responsible for applying our standards for high-level waste disposal, made a similar evaluation and also found that standards based on radioactivity release limits could be implemented more readily than standards based on exposures to individuals.

The proposed standards, although they do not directly limit doses to individuals, place requirements on disposal systems that make it unlikely that many individuals will be unduly exposed. The assurance requirements are intended to reduce the chance that a person will intrude into the disposal system. Furthermore, our analyses show that the containment requirements will limit the area of the environment that can become contaminated and, thus, reduce the probability of significantly exposing people who might inadvertantly disturb the lithosphere near the disposal site.

From these considerations, we believe that our proposed action will better facilitate licensing of good disposal systems while providing appropriate environmental protection from the long-term risks presented by these wastes. Therefore, we did not choose this alternative.

4.8 SET DIFFERENT LIMITS FOR RELEASES DUE TO NATURAL CAUSES AND FOR THOSE CAUSED BY PEOPLE

We could have set standards containing two sets of containment requirements: cumulative limits on releases due to natural processes and events and limits on releases from each individual event caused by human actions. The separate containment requirements would then better reflect the greater uncertainties involved in predicting human behavior.

For releases caused by natural processes and events, we would use numerical limits similar to those in the proposed standards. The probability of these releases would still have to be evaluated to determine the limits on total releases from all such events over 10,000 years. Based upon the analyses described in Chapter 5, we would make the release limits for "reasonably foreseeable" natural processes and events 10 times smaller than our proposed limits (which apply to both natural and man-caused releases). The limits for "very unlikely" releases would not change. The risk associated with these release limits would be about 200 excess cancer deaths over 10,000 years.

For releases caused by actions of humans, we could set numerical limits for all expected events or for any single intrusion. The analyses described in Chapter 5 indicate that a single intrusion could cause about 50 to 100 excess cancer deaths over 10,000 years. (This assumes that no one would clean up the radioactivity released and that it would disperse through the environment.) The limits would apply to those human actions the implementing agencies judge to be credible. The limits would not apply to recovery of the wastes for their resource value. We assume that people knowing enough about the wastes to want to recover them would also know about their dangers and would take appropriate precautions.

If the limits on releases caused by human intrusion were stated for all such expected events over the 10,000-year period, the standard would simply be the sum of limits on releases caused by natural events and by human intrusion, and the total limits would be essentially unchanged. The only real difference would be that the containment requirements would have two components, and each limit would have to be met separately. It would not resolve the uncertainty of the frequency of possible human intrusion. This approach could introduce unnecessary complexity and would not provide any additional public health protection.

If the release limits for human intrusion were stated on a single-event basis, it would be unnecessary for regulatory or implementing agencies to estimate the number of intrusions that would be expected over the assessment period. This would eliminate a major uncertainty in assessing the risks and in determining whether a proposed disposal system meets the containment requirements in the standards. The separate release limit standards would therefore be easier to implement.

Standards with release limits for each separate human intrusion do not, however, place a direct limit on the total estimated harm to future generations. If a disposal system were located so that human intrusion was quite likely, the risks from disposal of the wastes from 100,000 MTHM could be much larger than the limits proposed in our standards. (For example, our risk assessment assumes about 200 intrusions into the salt repository over 10,000 years. Release limits corresponding to 50 to 100 excess deaths per intrusion would then be associated with 10,000 to 20,000 excess deaths over 10,000 years). Implementation of this alternative would rely on qualitative judgments by the regulatory agencies; quantitative estimates of overall risk would not be required.

There are definite advantages and disadvantages to either of these two possible choices, and they represent two viable options. We decided to select the single set of containment requirements for our proposed standards. We believe the simplicity of the single set of values, which adequately protect the public health, outweigh the possible advantages of the dual requirements.

Chapter 5

PROJECTED HEALTH EFFECTS FROM DISPOSAL

This chapter is a synopsis of our assessment of the risks from disposal of high-level radioactive wastes in mined geologic repositories. We describe the model geologic repository and show how the released radionuclides reach the accessible environment and people. We also describe how we assess the risks to future generations. The results of the risk assessment are given in terms of the number of fatal cancers and of the number of genetic effects to be expected in the exposed population over 10,000 years or more. A more detailed description of the models used, with additional references, is provided in Appendix B.

Our assessment consisted of a number of steps. First, we defined the reference mined geologic repositories. We then analyzed various events or processes that could lead to releases of radionuclides from a repository and modeled the movement of those radionuclides through the geosphere to the accessible environment. From the probability of release and the associated consequence, we then calculated the resulting risk to the model population (assumed rather similar in demography to the present United States population) and summed the risks from all these releases over the first 10,000 years after repository sealing.

The results of the assessment depend on our assumptions about the performance of the repository and about the movement of radionuclides through the environment. To describe the behavior of each part of the disposal system, we chose performance values that we believe would be achievable by a carefully selected site and a well-designed repository. The numerical values that describe each physical, chemical, or biological process are given in Smith, et al. (SMC 82). The assessment then shows how the results depend on the various characteristics of the disposal system and which characteristics are most important.

We evaluated the risks from model repositories in five different geologic media: bedded salt, dome salt, granite, basalt, and shale. Our detailed discussion here concentrates on repositories in salt and granite, since these were found to give lower risks. For comparison, some results for basalt and shale repositories are also given.

5.1 MODEL REPOSITORIES

Our model repositories contain radioactive waste consisting of 100,000 metric tons of unreprocessed spent fuel, aged 10 years after removal from reactors. We chose spent fuel for our assessment because this requires examination of the behavior of both fission products and transuranium nuclides. The waste is assumed to be contained in canisters that would last 100 years in salt and 500 years in granite.

Figure 5-1 shows a model of the repository in bedded salt; Figure 5-2 shows a model of the repository in granite. Both reference repositories cover an area of 8 square kilometers, about one-fourth of which is

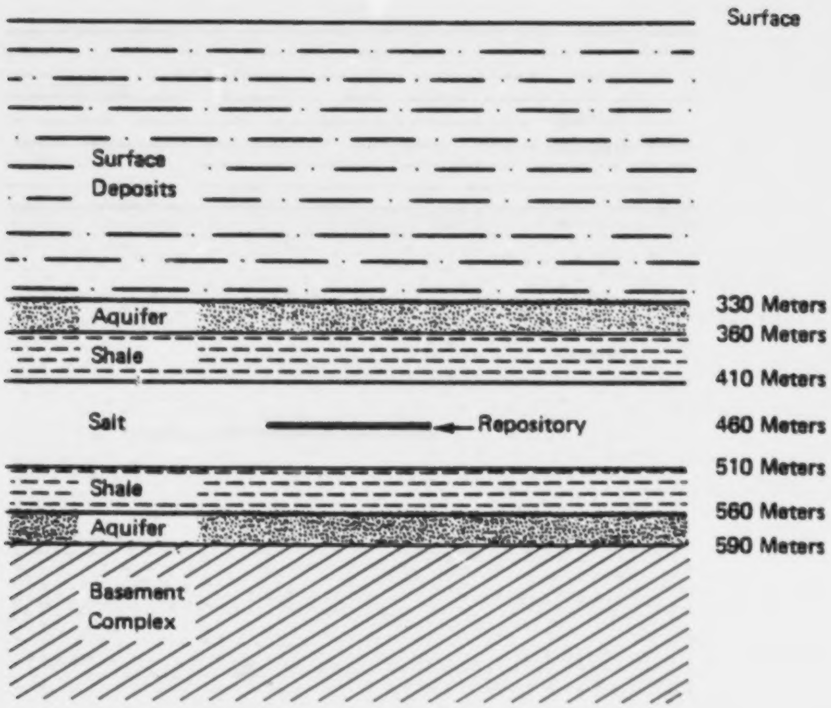
Surface
Surface Deposits
330 Meters
Aquifer
360 Meters
Shale
410 Meters
Salt
Repository
460 Meters
510 Meters
Shale
560 Meters
Aquifer
590 Meters
Basement Complex

FIGURE 5-1 REFERENCE REPOSITORY IN BEDDED SALT

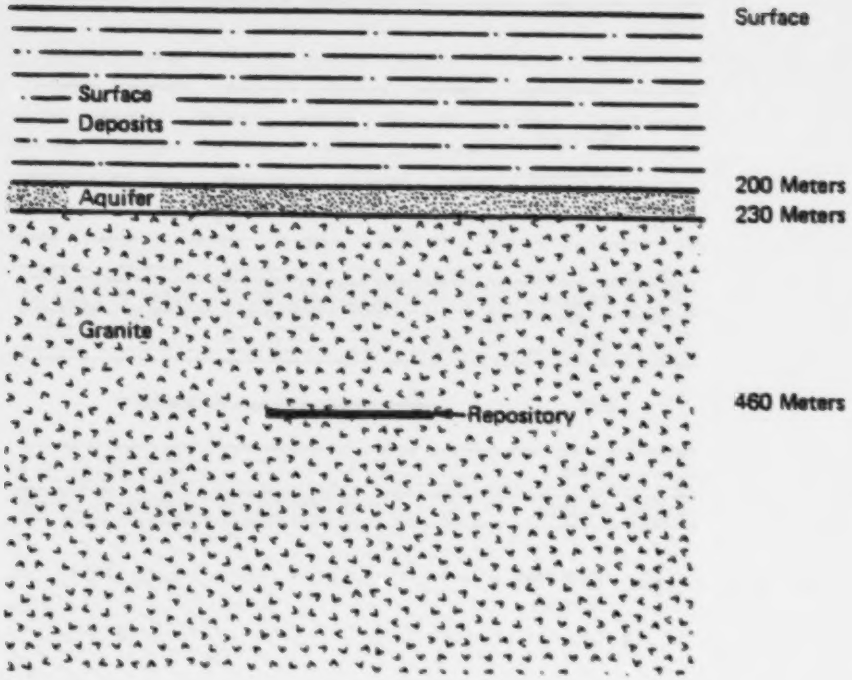
Surface
Surface Deposits
200 Meters
Aquifer
230 Meters
Granite
460 Meters
Repository

FIGURE 5-2 REFERENCE REPOSITORY IN GRANITE

actually mined. The reference repository in bedded salt is 460 meters below the surface. The salt layer is 100 meters thick, so there are 50 meters of impervious salt above and below the repository level. There are an additional 50 meters of relatively impermeable shale immediately above and below the salt; then there are overlying and underlying water-bearing permeable layers 30 meters thick. For convenience, we refer to these permeable layers as aquifers, although they may not be useable sources of groundwater. Above the upper aquifer is another 330 meters of overburden. The groundwater discharges into a stream 1600 meters from the repository site. The reference granite repository is also 460 meters below the surface. The granite formation continues indefinitely below it. Above it there is a 230-meter thickness of granite, and above this is a permeable stratum identical with the one modeled for the bedded-salt repository. Above this permeable stratum are 200 meters of overburden.

We assume that the material removed to construct the mined cavity will be returned as backfill after the wastes have been emplaced. This backfilled material cannot be compressed to its original density; we assume there will be void spaces amounting to 20 percent of the mined volume. Because the repositories are below the water table and cannot be completely sealed from groundwater, we expect that the void spaces will fill with water. In granite, this water enters from the upper aquifer through fractures in the rock and eventually fills all the void spaces in the backfill. In salt, it enters from the upper aquifer through imperfections in shaft and borehole seals. Much of the void space is eliminated by plastic movement of the salt, and only a small amount of water is trapped in the salt in the form of brine pockets.

As the canisters fail, the waste is exposed to water in the repository and is gradually leached from the matrix and dissolved. This contaminated repository water is the largest source from which radioactivity reaches the accessible environment. We selected a release rate[*] of 0.01 percent per year (10^{-4} per year) for the waste. We assumed that the uptake of nuclides of uranium, plutonium, neptunium, and technetium by groundwater was limited by their solubility, which was taken to be 1 milligram per cubic meter of water. We also assumed that the solubility of americium was 50 grams per cubic meter of water and that of tin was 1 gram per cubic meter. Nuclides of these elements represent the most important long-term concern in terms of movement through the environment and possible hazard to people.

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[*] "Release rate" is defined as the fraction of material dissolved from the high-level waste matrix by the surrounding liquid (water) during a given period of time. This rate generally determines the maximum rate at which any nuclide can enter the repository water.

We modeled the aquifer as a porous permeable rock. Water flows in the aquifer slowly, the speed being determined by the porosity[*] and permeability[**] of the rock and by the hydraulic pressure gradient in the aquifer. We assumed that the aquifer permeability is 10^{-4} centimeters per second (about 30 meters per year), the aquifer pressure gradient is 0.01, and the effective porosity is 0.15. This combination of permeability, flow gradient, and porosity corresponds to an interstitial water velocity[***] of about 2 meters per year. Nuclides reaching the aquifer will move in the direction of groundwater flow. A few nuclides will move at the same speed as the groundwater, but most will move more slowly. The extent to which a nuclide is slowed in comparison to the groundwater is expressed as a retardation factor.[****] We selected conservative retardation factors for the significant nuclides. These factors were 100 for actinides, 10 for tin, and 1 for other nuclides. The choice of these relatively small retardation factors means that the calculated values for movement along the aquifer flow are likely to be faster than will actually be observed.

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[*] "Porosity" is the fraction of the rock formation available to water (void fraction).

[**] "Permeability" is the ability of a geologic formation to transmit water.

[***] "Interstitial water velocity" is the speed of water flow through the rock or other medium.

[****] "Retardation factor" is the ratio of the interstitial water velocity to the velocity of the radionuclide. For example, a retardation factor of 100 means that the nuclide moves at 1/100 the speed of the water. Retardation is caused by adsorption or other mechanisms which slow the movement of chemical compounds through the environment.

5.2 RELEASE AND TRANSPORT MECHANISMS

Under an EPA contract, Arthur D. Little, Inc. (ADL) identified and analyzed possible processes by which the waste could be released from a repository (ADL 79). Once released, radionuclides could enter the environment via air, land surface, or groundwater pathways. The ADL study provides the basic information needed to describe the quantities of radionuclides released from the repository by each process or event, and the probabilities of release. The report includes estimates of the fraction of the repository affected by an event and of the groundwater flow rate through the affected area of the repository.

Radionuclides released directly to air or land surface reach the accessible environment quickly. Releases into groundwater can reach the accessible environment only after considerable delay. We applied a simple one-dimensional transport model of radionuclides in the groundwater. The model neglects dispersion, but includes the velocity of groundwater flow, retardation of nuclides, and solubility limits for certain nuclides.

Once the radionuclides enter the accessible environment, they can reach people through a number of pathways (SMJ 82). We considered a total of 30 of these pathways. For radionuclides reaching surface water, for example, we considered: (a) drinking water; (b) eating fish; (c) eating three types of foods grown by irrigation--surface crops, milk and beef; (d) breathing air contaminated by resuspension after irrigation; and

(e) standing on ground contaminated by irrigation. For each nuclide, the fraction eaten or breathed by humans from each pathway was calculated. Doses to those organs believed susceptible to radiation induced cancer were calculated, as well as doses to the reproductive organs. The doses to each organ were then summed over all pathways, including the external dose pathways. We then estimated the total numbers of fatal cancers and first generation genetic defects to the population. Risk conversion factors were derived from the report of the Committee on the Biological Effects of Ionizing Radiation (BEIR) of the National Academy of Sciences (NAS 72).* Table 5-1 summarizes our estimates of the fatal cancers caused by each curie of radioactivity released to the environment for each of the three release modes: to surface water (via groundwater), to the land surface, or to the air (SMJ 82).

We expect population distributions, food chains, and technology to change dramatically over 10,000 years. Unlike geologic processes, they can be realistically predicted only for short times. Accordingly, our estimates of health effects used general models of environmental pathways, populations, and living habits (SMJ 82). Rather than attempt to predict future changes in populations, cancer cure rates, etc., they assume present values for these parameters.

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*We have not recalculated these risk estimates on the basis of the July 1980 report of the BEIR committee (NAS 80). The risk estimates using the 1980 report would be somewhat lower, but not by as much as a factor of 10.

Table 5-1

Potential Health Effects (Fatal Cancers) Caused per Curie Released to the Environment by Different Modes

Nuclide	Releases to Surface Water	Releases to Land Surface	Releases to the Air
Am-241	0.73	0.09	0.16
Am-243	2.77	1.03	1.14
C- 14	0.05	0.00003	0.0002
Cs-135	0.004	0.0004	0.0007
Cs-137	0.02	0.0006	0.007
I-129	0.01	0.00002	0.001
Np-237	0.6	0.003	0.08
Pu-238	0.02	0.003	0.02
Pu-239	0.07	0.06	0.05
Pu-240	0.07	0.05	0.05
Pu-242	0.07	0.06	0.05
Ra-226	3.17	0.08	0.49
Sr- 90	0.12	0.001	0.02
Tc- 99	0.0003	0.00000006	0.00004
Sn-126	0.12	0.04	0.11

The risk from an event (e.g., movement of a fault or inadvertent human intrusion by exploratory drilling) is the probability of that event multiplied by its consequences. For each type of possible event, we estimated the probability of its occurence within several different time periods after disposal. We did this because the same event or process will release different amounts of radionuclides--because of radioactive decay--depending on the time when it occurs. We then estimated the consequences for each event occurring within each time period after repository sealing. We then added the risks from all individual events to obtain the total projected risk to the population.

5.3 RESULTS OF RISK ASSESSMENTS

5.3.1 Population Risks

For the reference bedded-salt repository, the projected number of fatal cancers in the first 10,000 years is about 100. Almost all of these are due to releases of contaminated water from the repository to the land surface as a result of drilling during resource exploration. For the reference granite repository, the projected number of fatal cancers in the first 10,000 years is about 700. Almost all of these result from transfer of contaminated granite repository water to the surface during drilling in the same way as for bedded salt. About 10 cancers are due to routine releases from natural processes, in which the heat generated by the waste is the driving force for a buoyancy pump, which raises repository water through the fractures in the granite to the permeable stratum, through which it is carried to surface water. Figure 5-3 shows the projected health effects over 10,000 years for each type of event that may affect granite or bedded salt repositories. Figure 5-4 provides a comparison of projected health effects for repositories in different geological media.

We also evaluated the health risks over longer periods, considering only the events and processes occurring in the first 10,000 years. In the granite repository, many nuclides remain in transit in the groundwater during the first 10,000 years, so that the expected number of fatal cancers increases to about 900 in 50,000 years and to 2,800 in 100,000 years. The corresponding number of fatal cancers from a bedded-salt repository increases only to 150 in the first 20,000 years and remains constant at this figure for 100,000 years.

To evaluate the effect of changing our assumptions, we also calculated results for different choices of the more important variables. Resistance of the waste to leaching and the insolubility of uranium, neptunium, plutonium, and technetium are important in limiting the risks from disposal. Both the nature of the waste form and the geochemical characteristics of the site determine leaching resistance and insolubility. Leaching and solubility change the availability of the radionuclides to the groundwater in the repository. Reduction of the leach rate by a factor of 100 per year from the reference case reduces the projected fatal cancers in granite to about 10; increasing the leach rate by a factor of 100 increases them to 2,500. Effects for the bedded-salt

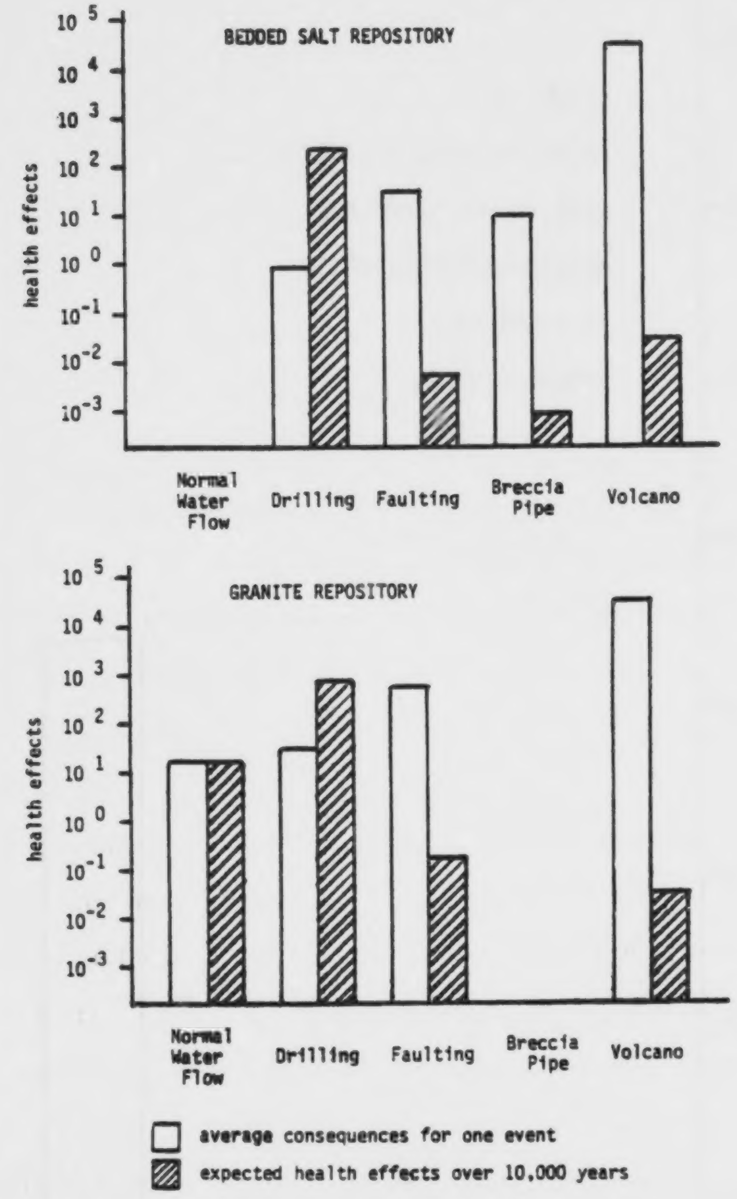

FIGURE 5-3: CONSEQUENCES AND RISKS FOR DIFFERENT EVENTS
(Bedded Salt and Granite)

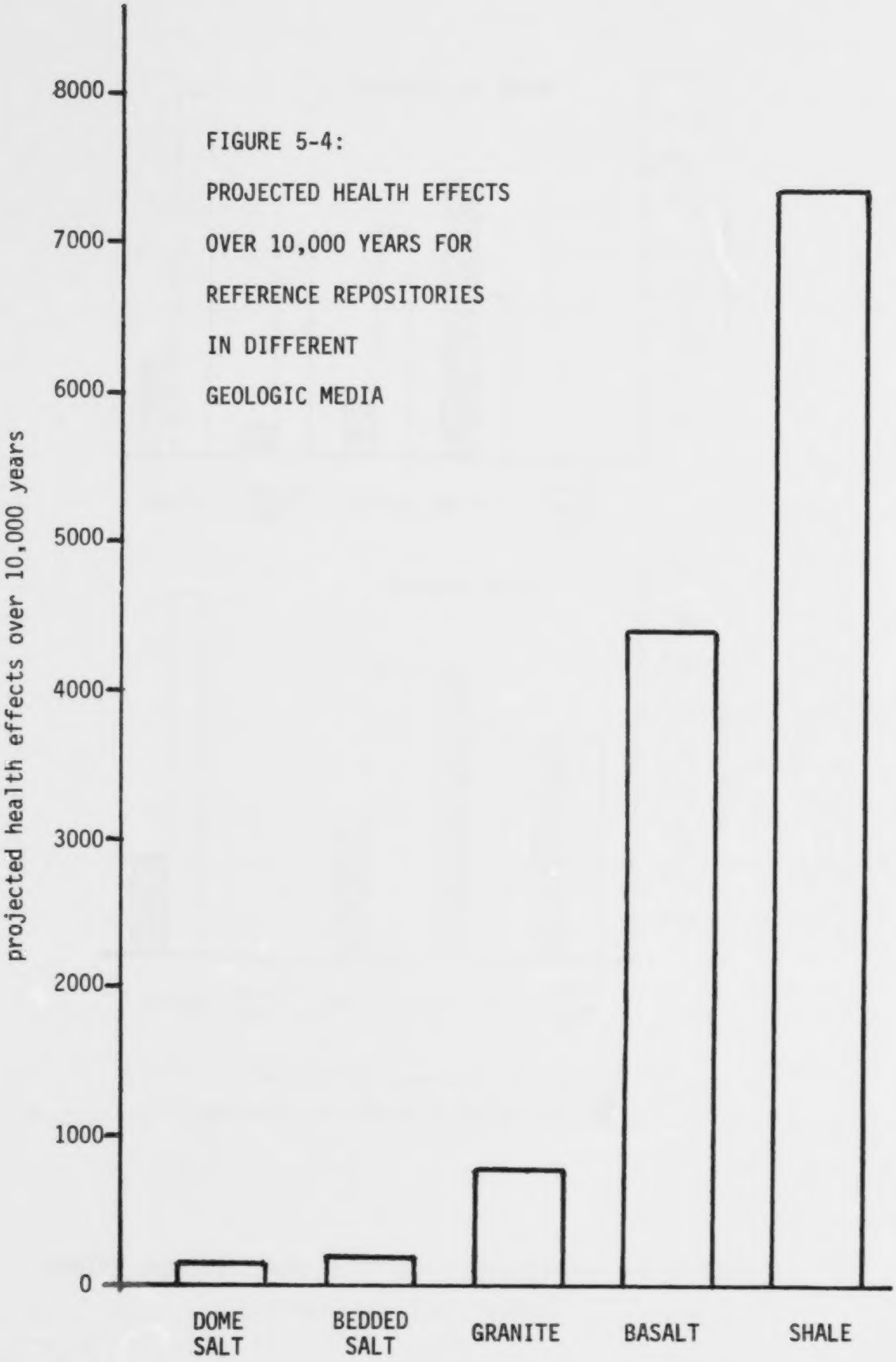

FIGURE 5-4:
PROJECTED HEALTH EFFECTS
OVER 10,000 YEARS FOR
REFERENCE REPOSITORIES
IN DIFFERENT
GEOLOGIC MEDIA

repository are much smaller. The effect of varying the leach rates is shown in Figure 5-5. The effects of assuming infinite solubility are shown in Figure 5-6. Eliminating the solubility limit for selected actinides and for technetium would increase the projected number of fatal cancers in the granite repository to almost 2,000, and in the bedded salt to 9,400.

The stability and durability of canisters are less important than resistance of the waste form. Modeling canister lifetime at 1,000 years produces relatively small decreases in the projected number of fatal cancers; modeling canister lifetime at 5,000 years reduces the number of projected fatal cancers by a factor of about five. Long-lived canisters, on the order of 50,000 to 100,000 years, would substantially reduce the number of fatal cancers because of decay of important nuclides, especially americium-243, while the containment existed. The effect of different assumptions on canister lifetime is shown in Figure 5-7.

Modeling all nuclides with retardation factors equal to one, so that all nuclides move with the speed of groundwater, increases the number of projected fatal cancers from the granite repository to over 30,000. Figure 5-6 shows the effects of assuming no retardation. Higher retardation factors, such as 10,000 for the actinides (except neptunium), do not significantly reduce the number of projected fatal cancers, since these radionuclides move so slowly through the environment.

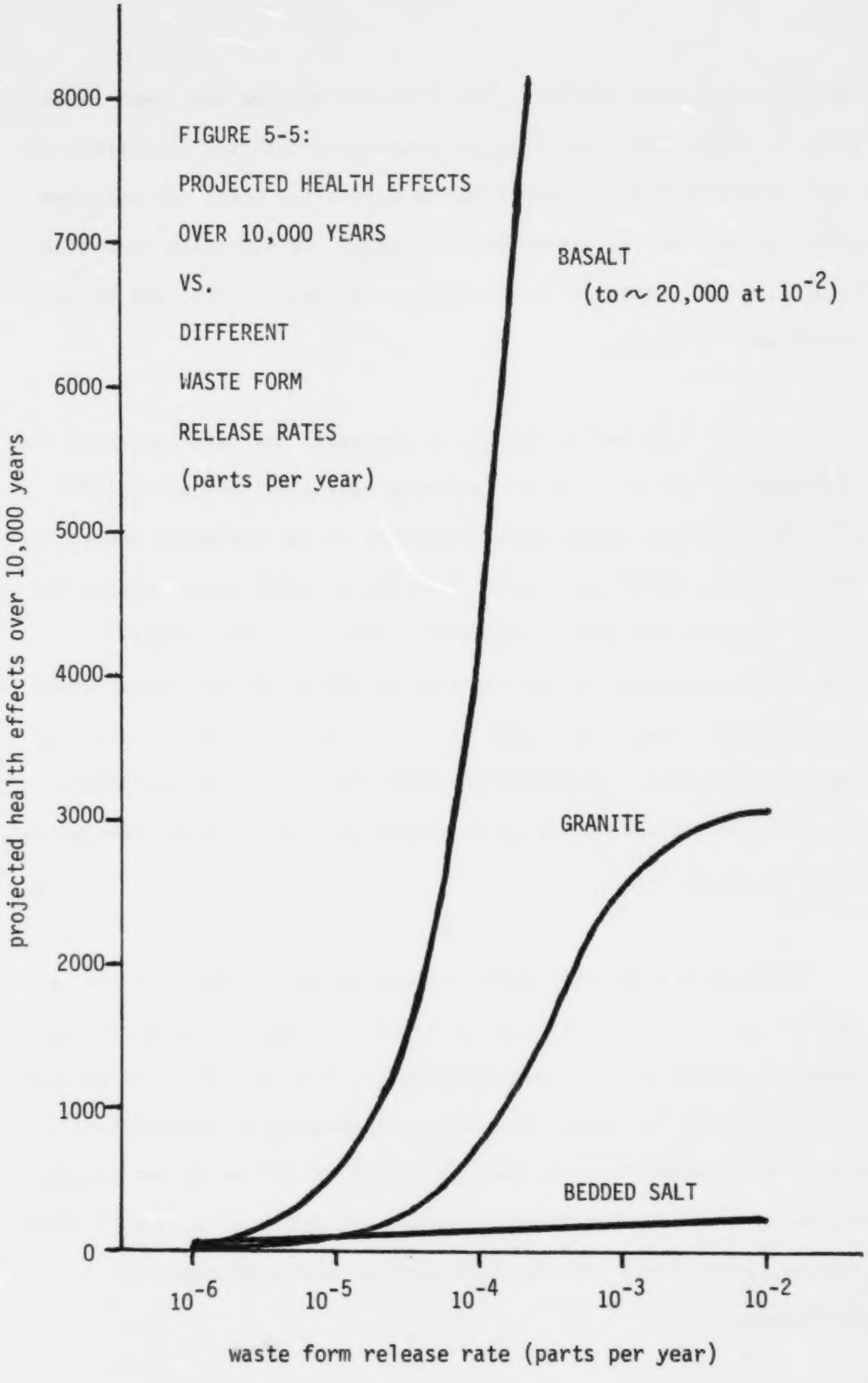

FIGURE 5-5:
PROJECTED HEALTH EFFECTS
OVER 10,000 YEARS
VS.
DIFFERENT
WASTE FORM
RELEASE RATES
(parts per year)

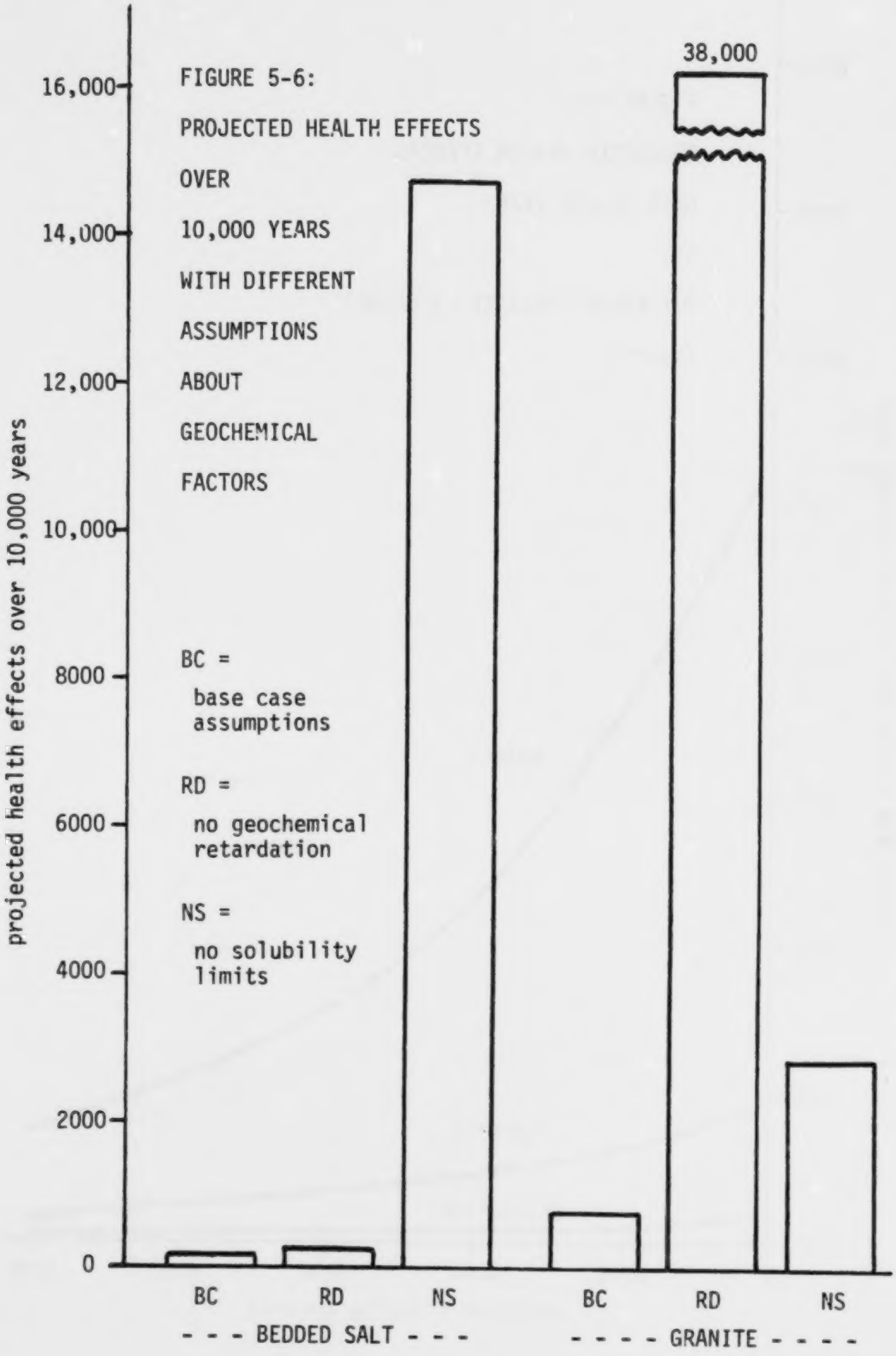

FIGURE 5-6: PROJECTED HEALTH EFFECTS OVER 10,000 YEARS WITH DIFFERENT ASSUMPTIONS ABOUT GEOCHEMICAL FACTORS

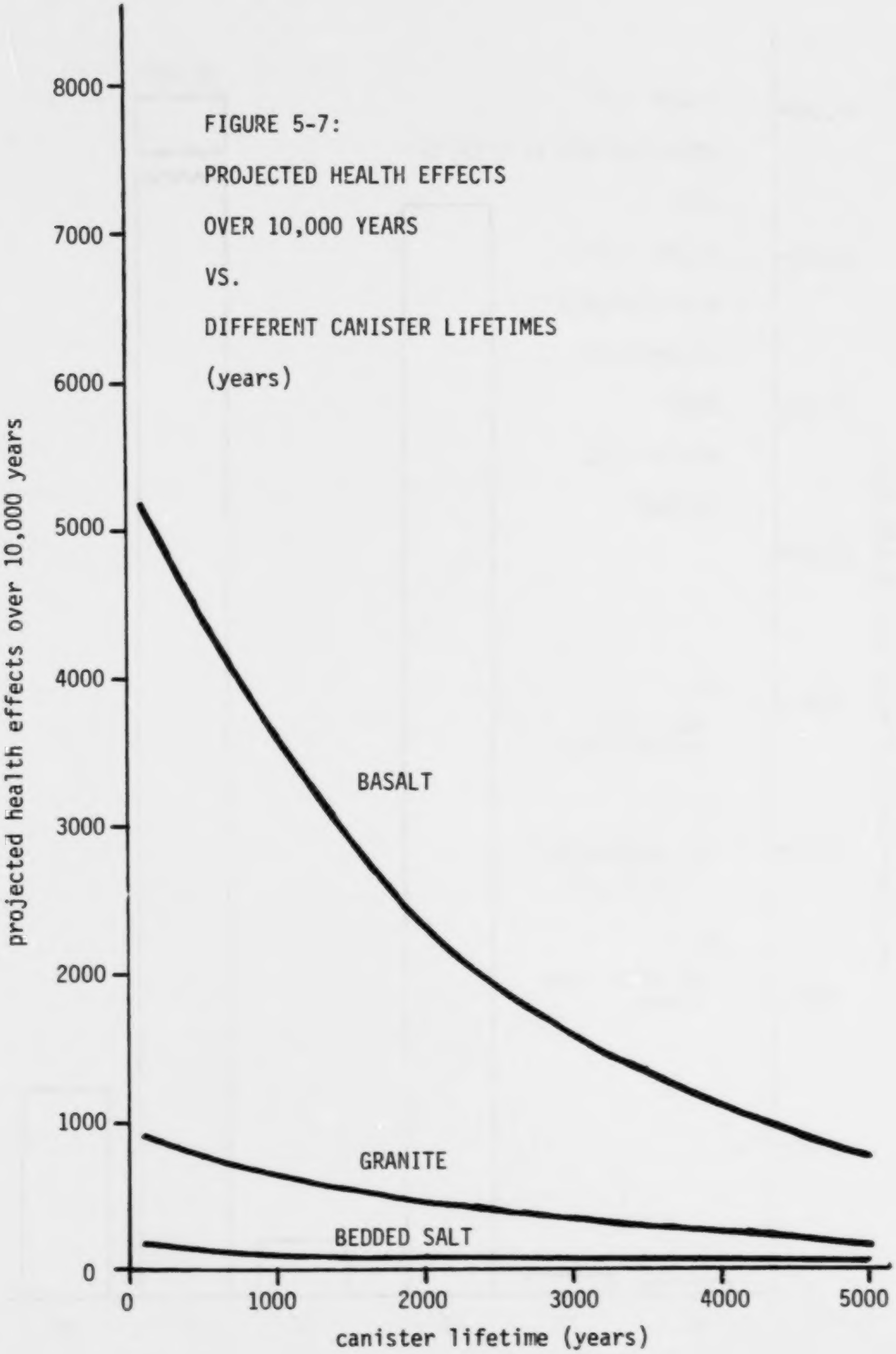

FIGURE 5-7:

PROJECTED HEALTH EFFECTS

OVER 10,000 YEARS

VS.

DIFFERENT CANISTER LIFETIMES

(years)

Most of the fatal cancers for the reference case are associated with intrusion into the repository by drilling; therefore, the number of fatal cancers is roughly proportional to the frequency of drilling. The frequencies suggested for such drilling events by ADL are one in 50 years for the bedded-salt repository and one in 400 years for the granite repository.

For the reference cases, the calculated first generation genetic effects are lower than the number of fatal cancers by a factor of more than 10. This is because most of the important nuclides involved are bone seekers and none concentrate in gonads or soft tissue.

5.3.2 Risks to Individuals

Without effective institutional controls, the probability that someone exploring for resources will drill into the repository at least once in the first 5,000 years is high, even at drilling frequencies significantly smaller than those estimated by ADL. The groundwater immediately above the repository would be contaminated by repeated drilling events, and some of it would remain contaminated for long periods of time.

Individuals may be exposed to nuclides released from the repository by breathing air contaminated as a result of releases of nuclides to land surfaces or by drinking water contaminated as a result of introduction of radionuclides into the groundwater (GO 82). Doses from breathing air were calculated as relatively small at distances of 100 meters or more from the point of discharge to the surface. Radionuclides move slowly in groundwater and exist in rather high concentrations over fairly small areas. The most important nuclides in groundwater are the americium isotopes 241 and 243. These nuclides, particularly the long-lived americium-243, persist for a long time in the environment.

We analyzed a scenario in which an initial drilling event directly contacted contaminated groundwater in a granite repository. This scenario results in the greatest contamination of the groundwater in the adjacent aquifer (GO 82). For each such hypothetical drilling event, contamination would spread slowly in the aquifer. By 1,000 years after the drilling, an aquifer area of about 4,000 square meters would be contaminated enough to give a dose of more than 500 millirems per year to people who might subsequently drill into the aquifer and drink the water. By 10,000 years after the initial drilling, an aquifer area of about 80,000 square meters would be contaminated to this level.

The probability that an individual would subsequently drill a water well into an area contaminated by resource exploration depends on conditions at the site, particularly the relative availability of contaminated and uncontaminated water. People are not likely to drill wells into a deep aquifer if adequate water is otherwise available. Using the following assumptions, we made a generic estimate of the probability that a person might encounter a contaminated area: about 500,000 water wells are drilled per year (GE 73), of which some 2 percent are deeper than 150 meters (500 feet). The U.S. Geological Survey (NW 79) estimates that about one-third of one percent of all wells are low-yield (less than 10 gallons per minute), deep (greater than 500 feet) wells. To allow for increased use of ground water in the future, we assume that 5,000 deep, low-yield wells are drilled in the United States each year. The number of new wells, divided by the U.S. land area of 7,800,000 km^2, is $6.4x10^{-10}$ new wells per square meter per year. The probability of a person drilling into an 80,000 square meter area (the area contaminated above 500 millirem/year at 10,000 years) would be about one in two-hundred during any 100-year period.

5.4 CONCLUSIONS

Our assessment of disposal in mined geologic repositories identifies the major factors in estimating risks to future generations. The following conclusions can be drawn from the assessment:

The release of a large fraction of the repository inventory should be extremely unlikely. In a deep-mined geologic repository, only a volcanic eruption or the impact of a large meteorite should produce a very large release of radionuclides (more than a few percent of the inventory). The chance of such releases occurring within 10,000 years is vanishingly small if the wastes are placed deep enough below land or water in a nonvolcanic area.

The movement of important radionuclides in groundwater from the repository to the accessible environment should be slow enough to provide substantial time for decay of radioactivity. Low permeability and a small hydraulic gradient in the groundwater stratum will result in slow groundwater movement. High adsorption is necessary to further slow the movement of such moderately long-lived radionuclides as plutonium-239, americium-241, and americium-243.

The entry of radionuclides into groundwater should be slow. Some radionuclides, particularly those of uranium, neptunium, plutonium, and technetium, can be kept essentially insoluble in groundwater by proper selection of their chemical form in the waste. We can select repository sites where the geochemistry will keep these elements in their insoluble forms. For other elements, selection of waste forms that are leached slowly should limit the rate of entry into groundwater even though the chemical forms of these elements in the waste are more soluble.

The chance that any individual will receive high doses should be small. High doses are associated with use of contaminated groundwater or air close to a point where radionuclides have been released. The probability of an individual receiving high doses can be made small by selecting sites where groundwater is not likely to be used, where there are no resources likely to be exploited, and where natural intrusive events are improbable.

In general, we have shown that it is reasonable to expect disposal of high-level radioactive wastes in a mined geologic repository (containing the wastes from 100,000 MTHM) to result in fewer than an average of one fatal cancer every 10 years for the first 10,000 years, provided the repository is reasonably well designed and well sited. Few of these health effects are expected to occur in the first 1,000 years after emplacement. The most important cause of radionuclide release appears to be human intrusion in the course of exploration for resources. Health effects may be reduced by using waste forms resistant to leaching and dissolving. More importantly, adverse effects will be reduced by selection of sites where: (1) the geochemistry will maintain technetium and most actinides in an insoluble form, (2) the hydrology will retain many nuclides in the groundwater for long times, and (3) exploration for resources is improbable.

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Chapter 6

PROPOSED STANDARDS FOR WASTE DISPOSAL

The proposed standards for disposal contain three sections: containment requirements, assurance requirements, and procedural requirements. The containment requirements set limits on potential releases of radioactive materials from disposal systems to the accessible environment for 10,000 years after disposal. These requirements are based on the assumption that our predictions of projected risks from disposal systems are good enough to use in selecting, designing, and implementing disposal methods. These predictions can then be used to assess the long-term releases from a disposal system and to decide whether it will provide adequate protection to present and future generations.

Closely coupled with the numerical containment requirements are seven qualitative assurance requirements that are needed to have confidence that the long-term release limits will be met. The assurance requirements address and compensate for the uncertainties that necessarily accompany plans to isolate high-level and transuranic wastes from the environment for a very long time. No matter how promising analytical projections of disposal system performance appear to be, these wastes should be disposed of in a cautious manner that reduces the likelihood of unanticipated releases. Our assurance requirements provide the context necessary for application of our containment requirements, and they should ensure very good long-term protection of the environment.

Finally, our procedural requirements provide instructions that must be followed to ensure that the containment requirements are properly implemented for particular disposal systems. These requirements describe the assumptions that are appropriate when assessing the performance of disposal systems to determine compliance with our long-term release limits.

In the following sections, we discuss the various features of all three sets of requirements, explain why we selected them, and describe how they should be used.

6.1. CONTAINMENT REQUIREMENTS

The primary requirements of our proposed environmental standards are numerical limits on the amount of radioactive waste that may be released from a disposal system to the accessible environment for 10,000 years after disposal. These containment requirements should provide excellent protection of public health and the environment. In fact, they should limit the risks to present and future generations to a level no greater than the risks from equivalent amounts of unmined uranium ore.

The following sections indicate how we selected the form of these containment requirements, why we chose the specific level of risk they are based on, and how the release limits are to be used. Because they address such a long time period, and because they include unplanned releases, these containment requirements can be implemented only through analytical projections of disposal system performance. There will be many uncertainties in making such long-term performance projections. Accordingly, our proposed standards require only a "reasonable expectation" that these containment requirements will be met; this determination must be made by the implementing agencies.

6.1.1 The Accessible Environment

The proposed containment requirements apply to releases to the "accessible environment," which we identify by a set of definitions:

> "'Accessible environment' includes (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) parts of the lithosphere that are more than ten kilometers in any direction from the original location of any of the radioactive wastes in a disposal system."
>
> "'Lithosphere' means the solid part of the Earth, including any groundwater contained within it."
>
> "'Groundwater' means water below the land surface in a zone of saturation."

Through these definitions we intend to protect all portions of the environment that may be in direct contact with man. (For example, the atmosphere, land surface, and any surface water directly over a geologic repository is included within the "accessible environment".) In addition, our definition of the "accessible environment" includes all groundwater formations that are more than 10 kilometers away from a disposal system. Groundwater is an important resource; currently, more than 20 percent of the fresh water used in the United States comes from underground sources. However, geologic formations that contain relatively small amounts of groundwater can serve as an important part of the containment system for a geologic repository. Thus, we need to allow for contamination of some groundwater while we are ensuring the long-term isolation of these wastes.

Accordingly, our approach does not provide any direct protection for the relatively small amount of groundwater that could be within 10 kilometers of a geologic repository. However, since the amount of groundwater left unprotected should be kept as small as possible, consistent with other requirements, we expect that the Federal environmental impact statement for each disposal system will identify all sources of groundwater within 10 kilometers of the disposal system, will describe the potential long-term environmental effects of possible contamination of these sources of groundwater, and will consider these effects as one of the factors in evaluating alternative sites.

On the other hand, our definition of "accessible environment" includes all groundwater sources--regardless of their quality--that are more than 10 kilometers away from a disposal system because our analyses indicate that this should be an ample distance to provide the protection expected from the geologic barriers of a repository. (In fact, all of the analyses described in Chapter 5 assume that the accessible environment, with respect to groundwater, is only 1 mile away from the repository--the longer distance of 10 kilometers would tend to reduce the residual risks identified in Chapter 5.)

6.1.2 Radionuclide Release Limits

The proposed containment requirements set limits on the projected releases of radionuclides to the accessible environment for 10,000 years after disposal. Because of the uncertainties of such long-term projections, we require a disposal system design to provide a "reasonable expectation" that the release limits will be met. A comprehensive performance assessment would be the basis for making this judgment.

These requirements would limit "reasonably foreseeable" releases to the quantities derived from Table 2 of the proposed standards: "Release Limits for Containment Requirements" (see Appendix A of this document). "Very unlikely" releases would be limited to 10 times the quantities for "reasonably foreseeable" releases. "Reasonably foreseeable" releases are those estimated as having a greater than 1 in 100 chance of occurring within 10,000 years. "Very unlikely" releases are those with a chance of occurring in 10,000 years estimated to be less than 1 in 100 but more than 1 in 10,000. We selected the qualitative terms "reasonably foreseeable" and "very unlikely" to emphasize that these are not precise estimates. The implementing agencies may use some discretion in assessing the probabilities of releases.

The values in Table 2 of the proposed standards are the quantities of each radionuclide that would result in 10 projected fatal cancers over 10,000 years (SMJ 82) if released into surface water--the most dangerous of the three release modes shown in Table 5-1. The values in Table 2 are expressed in terms of releases from wastes generated from 1000 metric tons of heavy metal (MTHM) originally placed in the reactor; they correspond to 1,000 projected fatal cancers in 10,000 years from the 100,000 MTHM geologic repository used in our risk assessment. We estimated that the long-term risks from disposal of wastes from 100,000 MTHM in our model repositories for salt and granite would be about 100 to 800 fatal cancers in 10,000 years. We choose release limits for Table 2 of the proposed standards that correspond to somewhat higher long-term risks.

We selected the value of 1 million curies of transuranic elements as a reference value for transuranic wastes to require about the same degree of control for the long-lived alpha-emitting radionuclides in transuranic wastes that we are requiring for those radionuclides in high-level wastes. Since a 100,000-MTHM repository contains about 300 million curies of transuranic nuclides, the 1,000,000-curie reference quantity for transuranic wastes is in about the same ratio to this total as the 1,000-MTHM reference quantity of spent fuel is with respect to the 100,000-MTHM model repository. Or, in other words, the reference values were selected so that about the same fraction of transuranic radionuclides would be retained for either high-level or transuranic wastes.

Since more than one nuclide would be released in any actual situation, the limitation for each nuclide must be lowered (made more stringent) to allow for the risks attributable to other nuclides. This is done through summing the terms:

$$a/A + b/B + c/C + \ldots$$

where a, b, c... are the cumulative releases of the various nuclides and A, B, C... are the appropriate Table 2 values. The total releases are summed over all radionuclides as well as over all release pathways.

The containment requirements provide for less stringent limitations on "very unlikely" releases of radionuclides to the accessible environment. They would set release limits that are higher by a factor of 10, with the requirement that the probability of such a release must be lower by a factor of 100. The requirement for a greater decrease in probability than the increase in released quantity reflects our aversion to large consequences. This provision amounts to about a 10-percent increase in effects on health.

These containment requirements do not permit large projected cumulative releases, which would have severe consequences, unless their probabilities are less than 1 in 10,000 over 10,000 years. Such large releases could result only from extremely disruptive events, such as a volcanic eruption or the impact of a large meteorite, occurring when the repository still contained a significant inventory of undecayed waste radionuclides. We do not believe that releases that are so highly improbable should be regulated.

6.1.3 The Level of Protection

We used the information in Chapters 3 and 5 to select a limit on harm to future generations that we believe is very small and that we believe good geologic repositories can meet. The limit on which we based our proposed containment requirements is 1,000 excess cancer deaths over 10,000 years for a 100,000-MTHM repository.

As shown in Figure 6-1 (which reproduces Figures 5-4 through 5-7 from Chapter 5, with the proposed level of protection indicated), there are several combinations of geologic media, engineered barriers, and site geochemistry that should provide at least this much protection. We believe, with careful site selection and with the technology available to develop engineered barriers, mined geologic repositories can keep risks below this level.

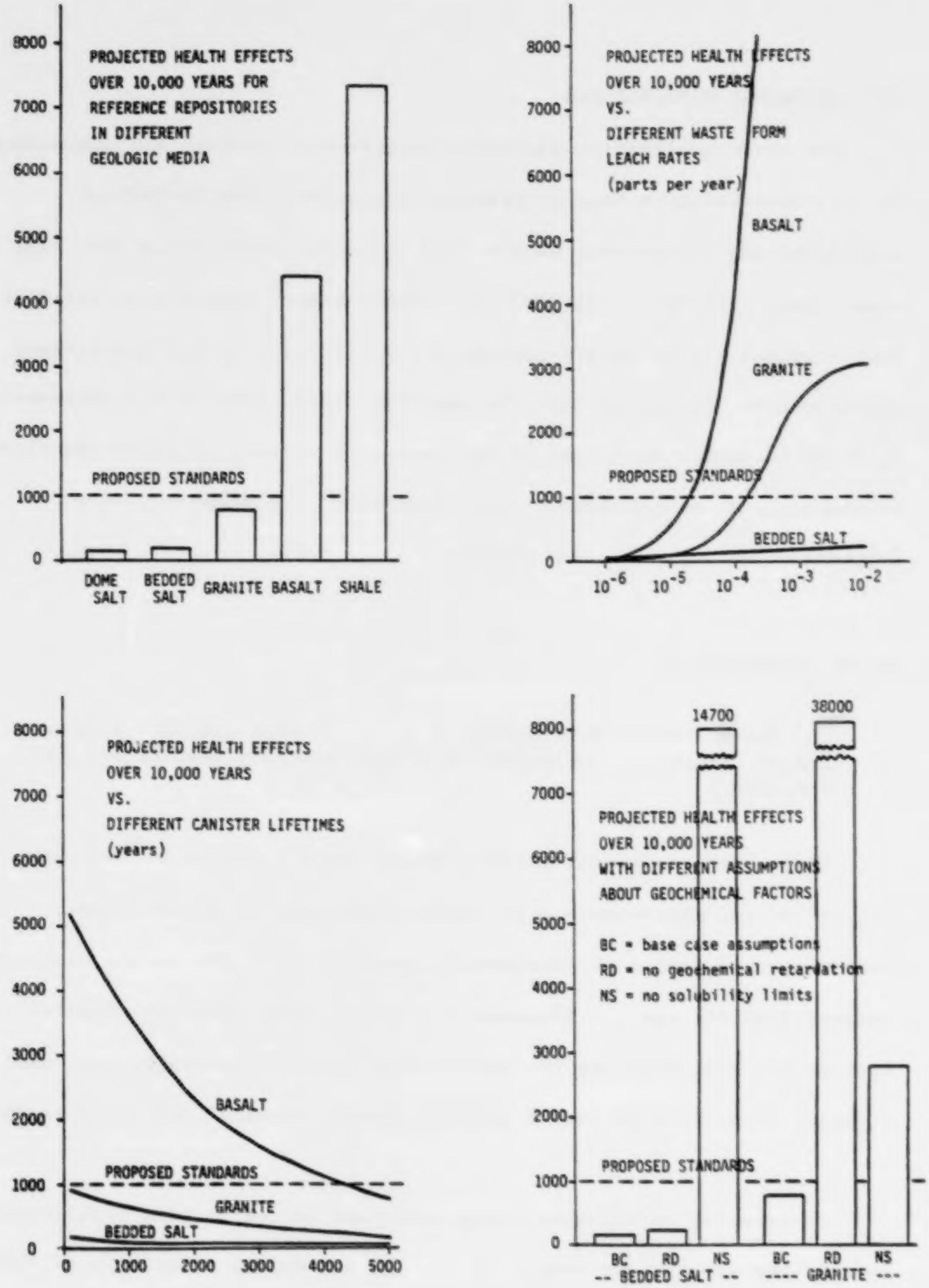

FIGURE 6-1: THE LEVEL OF PROTECTION

6.2 ASSURANCE REQUIREMENTS

Our seven qualitative assurance requirements address and compensate for the uncertainties that necessarily accompany plans to isolate high-level and transuranic wastes from the environment for a very long time. They call for a cautious and "common-sense" approach to disposal that provides the necessary context for application of our containment requirements. We expect that the specific steps taken by the implementing agencies to comply with each of the following criteria will be described in the Federal environmental impact statement--and other decision documents--for each disposal system:

6.2.1 Criterion 1:

> "Wastes shall be disposed of promptly once disposal systems are available and the wastes have been suitably conditioned for disposal."

Waste storage systems require active human controls for periodic inspection and maintenance. To reduce dependence on active human controls, this assurance requirement specifies that the wastes should be removed from storage and disposed of promptly once adequate disposal systems are available and the wastes have been appropriately processed for disposal (i.e., placed into a suitably stable chemical and physical form).

We have not established a specific time period in this requirement, because the appropriate length of storage may depend on details of the disposal system design. For example, it may be desirable to store high-level wastes for several decades to allow for decay of most of the short-lived radionuclides. The primary intent of this criterion is to prevent wastes from being stored indefinitely to avoid ultimate disposal.

6.2.2 Criterion 2:

> "Disposal systems shall be selected and designed to keep releases to the accessible environment as small as reasonably achievable, taking into account technical, social, and economic considerations."

As discussed in Chapter 2, we assume that any exposure to radiation can produce some harm. Accordingly, this assurance requirement stipulates that releases of radioactive wastes be kept as small as reasonably achievable. It instructs the regulatory agencies to reduce releases below the limits of the containment requirements on the basis of site- or method-specific information.

This principle has been used in radiation protection for a long time. It is not a totally quantitative concept, and we have not placed numerical specifications on it here. The technical judgment of the implementing agencies would determine when this criterion has been satisfied.

6.2.3 Criterion 3:

> "Disposal systems shall use several different types of barriers to isolate the wastes from the accessible environment. Both engineered and natural barriers shall be included. Each such barrier shall separately be designed to provide substantial isolation."

This assurance requirement emphasizes the need for caution in designing a disposal system by requiring multiple barriers. We will always be uncertain about how well a barrier may perform over the long lifetimes required of disposal systems. Furthermore, if a barrier in a disposal system fails, the failure would probably not be detected for a long time, if at all.

Therefore, the barriers should retain the radioactivity by different chemical and physical mechanisms. We believe that both engineered and natural barriers should be included. Each of the barriers should be designed separately to provide substantial isolation, even if the other barriers perform poorly. Extra barriers should be added when they can be provided at reasonable cost, even if they do not appear to be needed to meet the performance requirements for the overall disposal system.

6.2.4 Criterion 4:

> "Disposal systems shall not rely upon active institutional controls to isolate the wastes beyond a reasonable period of time (e.g., a few hundred years) after disposal of the wastes."

This assurance requirement would limit reliance on "active" institutional controls to a reasonable period after disposal, which should be no more than a few hundred years. "Active" institutional controls include guarding a disposal site, performing maintenance operations or remedial actions at a disposal site, or controlling or cleaning up releases from a disposal site.

This requirement does not mean we think society will lose all knowledge of radioactivity, nuclear energy, radioactive wastes, or even specific disposal sites after a few hundred years. On the contrary, we believe that such information is likely to survive, even without the extensive markers and records called for by the next assurance requirement. However, merely having this knowledge does not guarantee that it will be widely disseminated or effectively acted upon. We believe it is prudent to assume that society may not retain active controls over disposal systems for very long, and that unrelated activities may resume at a disposal site even though the presence of radioactive wastes is documented. The assumptions that we believe are appropriate when considering the effectiveness of "passive" institutional controls are described under our procedural requirements.

6.2.5 Criterion 5:

> "Disposal systems shall be identified by the most permanent markers and records practicable to indicate the dangers of the wastes and their location."

During our public workshops on radioactive waste criteria, we explored whether the location of radioactive wastes should be concealed from future generations or should be clearly marked (EPA 77). We became convinced that concealment was impractical because the inevitable anomalies of a disposal site would eventually attract attention. Therefore, trying to limit future knowledge would probably only make the situation more dangerous.

Accordingly, this assurance requirement calls for comprehensive actions to be taken to pass on information about the wastes and the way we disposed of them. However, we do not assume that this information can be guaranteed to prevent disruption of the site if active controls are lost. Unfortunately, warning signs of many kinds are often ignored today; we cannot assume they would be much more effective in the future.

6.2.6 Criterion 6:

> "Disposal systems shall not be located where there has been mining for resources or where there is a reasonable expectation of exploration for scarce or easily accessible resources in the future. Furthermore, disposal systems shall not be located where there is a significant concentration of any material which is not widely available from other sources."

This assurance requirement is a logical complement to our limitation on active institutional controls. Resources will attract exploration, and the people doing the exploring may not know of the locations or dangers of radioactive wastes. Since active controls may not be available to limit access, disposal systems should not be located where people are likely to explore for scarce or easily accessible resources.

Obviously, exploration may occur anywhere, and careful judgment must be used in applying this criterion. Past and current mining is an important indicator, but future trends must also be considered. Some resources that are not economical to recover today may become a substantial part of our resource base in the future; oil shales are an example of such a resource. Also, minerals not important now might become so in the future.

Because of these considerations, we believe that disposal systems should not be located where there is a substantial concentration of any material not widely available elsewhere. Nor should they be located where exploration or mining is likely in the future, particularly if related to resources that can be neither renewed nor significantly recycled (such as energy resources). This assurance requirement could also be important even if active institutional controls survive for a long time. A poorly located disposal system could deny or seriously hinder use of critical resources to future generations.

This assurance requirement should discourage the use of geologic formations frequently associated with resources. For example, salt domes are often mined either for their relatively pure salt or for use as effective, inexpensive storage caverns. Of the 130 domes in the Gulf Coast area judged suitable for such exploitation, 48 were in use as of 1965 (GR 81). As discussed under Criterion 4, we do not believe that active institutional controls should be relied upon to prevent exploration for resources for more than a few hundred years after disposal. Therefore, the frequent use of salt domes as resources would argue against locating a repository in this type of structure.

These particular concerns generally would not apply to bedded-salt deposits, which are far more extensive. A specific site in a bedded-salt deposit appears much less vulnerable to inadvertent intrusion than a particular site in a salt dome.

6.2.7 Criterion 7:

> "Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal."

This assurance requirement would permit corrective action if development of technical and scientific knowledge should indicate that a disposal system poses much greater risks than had originally been expected. High-level radioactive waste disposal is a new technology. Future generations may find it necessary or desirable to recover the wastes and change the disposal site or methodology in light of new knowledge.

This requirement is different from the more familiar concept of retrievable storage. Recovering the wastes after the conventional retrieval period of a few decades is likely to be expensive and, perhaps, even dangerous. It could require, for example, mining the entire repository volume to recover the wastes. This criterion merely requires that this option be left open to our successors.

Current plans for mined geologic disposal would comply with this assurance requirement. However, methods involving irreversible incorporation of radionuclides into disposal sites would not. Deep-hole placement, rock-melting, or hydrofracturing are examples of disposal methods that do not appear to comply with this assurance requirement.

6.3 PROCEDURAL REQUIREMENTS

Compliance with our containment requirements will be determined through long-term projections of disposal system performance. The "performance assessments" used to make these judgments should be done in accordance with the proposed definition included in our disposal standards:

> "'Performance assessment' means an analysis which identifies those events and processes which might affect the disposal system, examines their effects upon its barriers, and estimates the probabilities and consequences of the events. The analysis need not evaluate risks from all identified events. However, it should provide a reasonable expectation that the risks from events not evaluated are small in comparison to the risks which are estimated in the analysis."

When our containment requirements are applied to a particular disposal system, some of the procedures we used in our performance assessments (described in Chapter 5) must be retained so that the intent of our standards is met. On the other hand, some of the assumptions we made should be replaced with specific information appropriate for each disposal system. Our procedural requirements set forth three instructions needed to ensure that performance assessments for particular disposal systems are properly evaluated against the containment requirements. Each of these three procedural requirements is discussed here:

> "The assessments shall consider realistic projections of the protection provided by all of the engineered and natural barriers of a disposal system."

In developing the containment requirements, we considered the overall protection that should be achievable by the combination of barriers in a geologic repository. Accordingly, the analyses used by NRC and DOE to evaluate compliance with our requirements should consider realistic assessments of the protection provided by all of the engineered and natural barriers of a disposal system. For example, performance assessments of a geologic repository system should include the protection afforded by geochemical retardation of radionuclides and by the limited solubility of radionuclides in groundwater, provided that reasonable evidence is developed to support such mechanisms for that particular site.

> "The assessments shall not assume that active institutional controls can prevent or reduce releases to the accessible environment beyond a reasonable period (e.g., a few hundred years) after disposal. However, it should be assumed that the Federal Government is committed to retaining passive institutional control of disposal sites in perpetuity. Such passive controls should be effective in deterring systematic or persistent exploitation of a disposal site, and it should be assumed that they can keep the chance of inadvertent human intrusion very small as long as the Federal Government retains such passive control of disposal sites."

The assumptions we made in our performance assessments about the frequency of human intrusion were conservative because they ignored the substantial protection that passive institutional controls should offer. The performance assessments made for specific sites by the implementing agencies do not need to be as pessimistic with regard to human intrusion. Because of the uncertainties of controls requiring the active participation of people over a long time, performance assessments should not assume that active institutional controls can prevent or reduce releases beyond a reasonable period of time (e.g., a few hundred years) after disposal. However, because the Federal Government is committed to retaining control over these disposal sites in perpetuity, passive institutional controls should substantially reduce the chance of inadvertent human intrusion well beyond this period. These passive controls should not be assumed to prevent all possibilities of inadvertent intrusion, because there is always a chance that the controls will be overlooked or misunderstood. However, such measures should be effective in deterring systematic or persistent exploitation of a disposal site. Furthermore, the chance of human intrusion should be very small as long as the Federal Government retains passive control of disposal sites.

> "The assessments shall use information regarding the likelihood of human intrusion, and all other unplanned events that may cause releases to the accessible environment, as determined by the implementing agency for each particular disposal site."

We based our performance assessments on relatively simple generic models of geologic repositories and the data that was available for such models. Where information was uncertain, we made conservative assumptions that should tend to overestimate the long-term risks of disposal. However, we do not intend that the implementing agencies should use all of the same models, data, and assumptions that we did in making performance assessments. Instead, the implementing agencies generally should use the best information available for each particular disposal site.

Chapter 7

PROPOSED STANDARDS FOR WASTE MANAGEMENT AND STORAGE

Subpart A of the proposed standards establishes limits on the annual dose equivalent to any member of the public as the result of the management and storage of spent fuel and high-level and transuranic wastes. Management and storage operations for these materials include all treatment and handling preparatory to disposal, including storage, processing, packaging, and emplacement in the final disposal configuration. Transportation is not included (see Section 2.6.1).

Selection of a disposal technology defines the nature of the operations necessary before disposal. Several disposal technologies have been proposed, such as geologic, extraterrestrial and transmutation. These technologies have been reviewed for us by the MITRE Corporation (AL 79a) and for the President by the Interagency Review Group (IRG 79).

7.1 WASTE MANAGEMENT OPERATIONS FOR VARIOUS DISPOSAL OPTIONS

7.1.1 Operations for Disposal of Unprocessed Spent Fuel

Disposal of unprocessed spent fuel is applicable only to commercial power generation; defense fuel is reprocessed for recovery of weapons grade plutonium and for its highly enriched uranium content. Initial storage of commercial spent fuel at the reactor site is required to reduce radioactivity and heat generation by decay before further handling is attempted. Additional storage after packaging may or may not take place, depending on the availability of a disposal site. The management of unprocessed spent fuel prior to terrestrial disposal includes: storage before packaging (if required), packaging, additional storage after packaging, and emplacement.

Storage Before Packaging

Almost all spent fuel is now being stored, and considerable quantities have been stored for a number of years. This storage experience has provided considerable information on environmental impacts.

The Uranium Fuel Cycle standards (40 CFR 190) regulate storage of spent fuel at nuclear power stations. These proposed standards apply to storage at independent spent fuel storage facilities (ISFSF), which are not located at the reactor sites. This is sometimes referred to as away-from-reactor (AFR) storage. The Department of Energy (DOE) estimates the major releases from an ISFSF, in which 3000 metric tons of heavy metal (MTHM) have been stored in water basins for 6.5 years, to be about 890 curies of krypton-85 and 2.4 curies of tritium, per year. Almost all of the krypton releases and about half of the tritium releases occur at the time the spent fuel is received (HO 80a; DOE 79). The projected krypton-85 releases are small compared to the 50,000 curies per gigawatt (electrical)-year (GWe-y) permitted under the standards of 40 CFR 190, since 3000 MTHM corresponds to about 90 GWe-y, based on 33,000 megawatt (thermal)-days per metric ton and an electrical efficiency of 32 percent.

We estimated that the annual dose to a maximally exposed individual from the ISFSF (including dose associated with packaging) is 0.0006 millirem (mrem) to the whole body; the highest dose to any organ of an individual is 0.015 mrem per year to the thyroid. DOE estimates the aggregate annual doses to the population within 80 kilometers of a generic ISFSF, including the dose from a packaging operation, to be 0.47 organ-rems to the thyroid and 0.025 person-rems, whole body (DOE 79).

Packaging

Packaging spent fuel for final disposal is assumed to be carried out at the storage site rather than at the final disposal site. We estimate the major releases from packaging are 810 curies of krypton-85 and 1.3 curies of tritium per year (HO 80a; DOE 79). The individual and population doses are included in the ISFSF doses.

Extended Storage

We estimate that releases during recovery and handling of packaged spent fuel stored for 30 years are about 0.01 curies of krypton-85 and about 0.1 microcuries of tritium per year (HO 80a; DOE 79). Doses to any organ of a maximally exposed individual are less than 1 microrem per year; population doses are also negligible.

Emplacement

Releases of waste materials during emplacement occur only during the handling of waste packages. DOE estimates these releases to be about 10^{-20} curies per year (DOE 79) . Resulting doses, both individual and population, are below the 40 CFR 190 standards.

Naturally occuring radionuclides are released from repository materials during construction and operation. However, the resulting doses to individuals and populations are very small (DOE 79). These releases are not considered further, since they are small and are not significantly affected by these standards.

7.1.2 Operations Prior to Disposal of Processed High-Level Wastes

The management of processed high-level wastes prior to terrestrial disposal includes five steps (HO 80a):

1. High-level liquid waste (HLW) storage
2. Waste solidification
3. Interim storage of solidified waste
4. Emplacement
5. Treatment and emplacement of retained krypton-85 and iodine-129

High-Level Liquid Waste Storage

High-level liquid wastes result from defense activities and would also result from the reprocessing of commercial spent fuel if reprocessing were undertaken. The technology for storing high-level liquid wastes is based on 30 years' experience with defense wastes. Wastes are stored in subsurface tanks of stainless or mild steel. It is expected that stainless steel tanks will be required for the storage of high-level wastes from reprocessing commercial spent fuel (DOE 79). Double containment reduces the possibility of leakage to soil.

DOE has estimated the releases from a commercial reprocessing plant with an annual capacity for treating 1140 cubic meters (300,000 gallons) of high-level waste from 2000 metric tons of heavy metal. This is the spent fuel that corresponds to about 60 GWe-y. About 27,000 curies of tritium per year are estimated to be released to the atmosphere, while releases of any other nuclide would be about 1 millicurie per year or less. DOE calculated the maximum annual dose equivalent to any individual to be about 0.1 millirem and the population dose within an 80-kilometer radius to be about 11 person-rems.

Waste Solidification

In the event that commercial reprocessing of spent fuel becomes a part of the national program, Nuclear Regulatory Commission (NRC) regulations (10 CFR 50, Appendix F) require that the high-level liquid wastes generated from this reprocessing be converted to a solid form within 5 years and be transferred to the Federal Government within 10 years of its generation. Some alternatives proposed for long-term management of defense wastes also include waste solidification (ERDA 77a; ERDA 77b; ERDA 77c). Calcination is the most likely method of solidification prior to incorporation into a solid matrix, while glassification provides a solid matrix for disposal. The Idaho National Engineering Laboratory has calcined high-level wastes since about 1963, and Hanford has been developing various glassification techniques since the early 1960's.

We have assessed the environmental effects of calcination followed by glassification (HO 80b). The study considered fluidized-bed or spray calcination followed by in-can or continuous-melter glassification. Other treatments are possible, including formation of crystalline (e.g., synthetic rock or metal) matrices. Effluent releases from a generic plant using available or near-term available effluent cleaning technology were calculated. The assessment covered the seven radionuclides (tritium, iodine-129, ruthenium-106, cesium-134, cesium-137, strontium-90, and plutonium-239) most likely to be released during normal operations of the four potentially useful technologies available for calcination and glassification. We reviewed the control technology for particulates and for off-gas cleanup, estimated decontamination factors for typical off-gas control equipment for the radionuclides under consideration, and we estimated the overall system decontamination factors for iodine, ruthenium, and particulates to be 1×20^3, 1×10^7, and 1×10^{10}, respectively.

Radioactive effluent releases from the generic solidification plants were calculated for two locations, a rural site typified by Barnwell, South Carolina, and an urban site typified by St. Louis. Dose equivalents for whole-body and several organs were calculated for the maximally exposed adult at each location. Results are summarized in Tables 7-1 and 7-2. The largest organ dose was determined to be to the lower large intestine (LLI). Ruthenium-106 is the major dose contributor for materials up to one year old. As ruthenium-106 decays, tritium become the most significant nuclide in the older material.

Population doses were calculated for the areas within an 80-kilometer radius of the generic plant at each site. Results are provided in Table 7-3. Seven pathways were considered: air submersion, water submersion, surface contamination, inhalation, and ingestion of vegetables, meat and milk.

A number of factors contribute to the high population dose at the urban site. There are about 2.5 million persons within 80 kilometers of the urban site and about 0.5 million within the same distance of the rural site. There also are larger numbers of meat animals (about 700,000 versus 200,000) and dairy animals (about 38,000 versus 14,000) and more vegetable food crops produced (about 120,000 metric tons versus 30,000 metric tons) within 80 kilometers of the urban site. Meteorological factors also contribute to the higher dose at the urban site.

Interim Storage of Solidified Waste

Interim storage of solidified wastes would cause releases similar to those for extended storage of spent fuel, which was found to have negligible impact. DOE and EPA have estimated that the storage of

Table 7-1

Estimated Dose Equivalents to the Maximally Exposed Individual from Solidification
(Rural Site)

	Total Body (millirem per year)			Lower Large Intestine (millirem per year)		
	1 yr	5 yr	10 yr	1 yr	5 yr	10 yr
^{3}H	0.5	**	0.3	0.5	**	0.3
^{106}Ru	1	**	0.0	16	**	0.1
ALL	2	**	0.4	20	**	0.4

Table 7-2
Dose Equivalents to Maximum Individual from Solidification
(Urban Site)

	Total Body (millirem per year)			Lower Larger Intestine (millirem per year)		
	1 yr	5 yr	10 yr	1 yr	5 yr	10 yr
^{3}H	1.6	**	1.6	1.6	**	1.9
^{10}6Ru	8.7	**	0.1	130	**	0.3
ALL	11	**	2.2	140	**	2.4

Table 7-3
Population Doses from Waste Solidification

	Rural Site		Urban Site	
	Total Body (Person-rem)	LLI (Organ-rem)	Total Body (Person-rem)	LLI (Organ-rem)
1 yr	23	100	200	800
5 yr	8	11	90	100
10 yr	6	6	40	50

** not calculated

solidified waste would have even smaller impact, since krypton-85 and tritium, the only nuclides released in any quantity from spent-fuel storage, are not contained in the solidified waste.

Emplacement

Emplacement of solidified wastes is essentially the same process as emplacement of spent fuel. The doses estimated by DOE are extremely small (DOE 79).

7.1.3 Collection and Disposal of Krypton-85 and Iodine-129 Wastes

Under our environmental standards for the Uranium Fuel Cycle (40 CFR 190), krypton-85 and iodine-129 are considered to be wastes that must be collected for disposal. The doses from krypton-85 and iodine-129 releases occurring at fuel reprocessing plants have been examined in detail in connection with the development of the standards in 40 CFR 190. Therefore, we undertook further analysis of only the doses associated with these nuclides after removal from the reprocessing plants.

Krypton-85 Collection and Disposal Options

Our review indicates a number of collection methods suitable for krypton-85 (AL 79b). A model reprocessing plant would separate 12.7 million curies of krypton-85 from spent fuel as krypton gas. This gas would be contained in cylinders, either as pressurized gas or adsorbed on zeolite molecular sieves. Immobilization by ion implantation is being investigated but has not been as fully developed as the other techniques. Either engineered storage or geologic disposal is suitable for final disposal of the collected krypton.

DOE has estimated krypton leakage of 0.1 percent per year from storage in cylinders as a pressurized gas (DOE 79). The gas may be stored onsite for eventual release to the atmosphere. For this disposal option, these releases would be in addition to discharges from normal operation. Under these conditions it would require about 52 years to meet the Uranium Fuel Cycle Standard limit of 50,000 curies per GWe-y. Disposal in a mined geologic repository would provide smaller total releases, provided the containers were sufficiently stable in the mine environment to prevent increased leakage.

Iodine-129 Collection and Disposal Options

We also reviewed collection and disposal methods for iodine-129 (AL 79b). A generic reprocessing plant separates about 66 curies of iodine-129 per year in a total of about 600 to 650 kilograms of iodine. The iodine can be immobilized either as insoluble barium iodate in concrete or by sorption on zeolites. The immobilized iodine would then be suitable for terrestrial disposal, although extraterrestrial or seabed disposal options are being considered.

No detailed characterization of the effects associated with preparation of iodine-129 for final disposal is available. However, these effects can be compared with the effects of similar treatments of low-level and intermediate wastes, which are insignificant (DOE 79).

7.1.4 Extraterrestrial Disposal

Chemical processing is required if spent fuel is to be reprocessed and is also required for transmutation and extraterrestrial disposal. Both transmutation and extraterrestrial disposal of entire spent-fuel elements appear to be impractical because of the amount of material involved. Chemical processing is required to separate the long-lived radionuclides from the shorter-lived elements. This reduces the material to be transmuted or disposed extraterrestrially. DOE has prepared environmental assessments of conventional disposal technologies for spent fuel and for chemically reprocessed high-level liquid wastes (DOE 79, DOE 80). Limited descriptions of the environmental effects of technologies for extraterrestrial disposal and transmutation are available (AL 79a, DOE 80).

DOE and EPA analyses of the operations required to prepare high-level waste for extraterrestial disposal indicate that separation of the actinide fraction of the wastes (partitioning) would be required to avoid an excessive number of launches of space vehicles (AL 79a). After separation, nonactinide wastes would be disposed by terrestial methods. The separated actinide wastes would be packaged to make a waste form resistant to dispersion in the event of a launch accident or failure to achieve proper orbit. In some schemes, iodine-129 and other long-lived fission products would also be sent into space.

There is insufficient information for a detailed environmental analysis of the release of radionuclides during preparation for extraterrestrial disposal and in the event of accidents during launching (AL 79a; DOE 80). Since partitioning of actinides is a chemical operation similar to fuel reprocessing, it is reasonable to expect somewhat similar releases.

7.1.5 Transmutation

Transmutation is the conversion of radionuclides into other stable or radioactive nuclides, usually by irradiation with neutrons. Our review of this disposal option indicates that it is in the early conceptual design stage and that there is no firm information on potential releases or doses (DOE 79). The process requires that the nuclides to be transmuted be separated from the other materials. The actinides must be partitioned, and it is usually necessary to further separate individual actinides (fractionation). The actinides are then incorporated into fuel rods for the irradiation. The requirements for transmutation are similar to known processes in the nuclear fuel cycle--partitioning and fractionation are similar to fuel reprocessing, and incorporation of actinides into fuel rods is similar to fuel fabrication.

7.1.6 Other Separations

There have been many proposals for separation of various nuclides preparatory to waste disposal (DOE 80): separation for special disposal of long-lived nuclides (e.g., iodine-129, carbon-14, technetium-99) and separation of short-lived nuclides, particularly strontium-90 and cesium-137, to minimize heat loading for geologic disposal. Other proposals include more complete separations of lanthanides and actinides for space disposal or chemical synthesis of a waste form. None of these proposals is beyond the conceptual stage, and no information on environmental releases or effects is available. All of these separation techniques are chemical processes similar to fuel reprocessing.

7.2 DERIVATION OF THE STANDARDS

Our review of the waste management operations to be undertaken prior to terrestrial disposal reveal that it is feasible, with available technology and proper siting of facilities, to limit maximum individual doses to those established by the Uranium Fuel Cycle Standard (40 CFR 190). Many of the processes to be undertaken are similar to processes regulated under 40 CFR 190. Therefore, we are confident these processes can be regulated within these limits. The individual doses from some chemical processes have not been fully evaluated, but we believe that they can be expected to fall in the range of those associated with fuel reprocessing plants. Storage operations for collected krypton-85 and iodine-129 are also found to be within 40 CFR 190, although special provisions must be made for adequate time of decay before releasing krypton to the atmosphere.

Although we have little information on the waste management operations required for extraterrestrial disposal and transmutation, we believe the limit established under 40 CFR 190 will not preclude these options.

7.2.1 Selection of Standards Format

The proposed standards for waste management operations are expressed in terms of limits on annual radiation dose to individuals and to body organs. This is the format used in our environmental standards for the Uranium Fuel Cycle, 40 CFR 190.10(a). For a number of reasons, it is desirable to express the waste management operations standard in the same format, unless further investigation shows this format is unsuitable:.

1. The Uranium Fuel Cycle standards are conceptually simple and relatively easy to implement.
2. Many of the procedures covered by the waste management operations standard are similar to operations covered by the Uranium Fuel Cycle standards.
3. It is possible that facilities regulated by the waste management operations standard will be sited adjacent to, or in proximity to, facilities regulated under the Uranium Fuel Cycle standards. It would simplify procedures to use the same format in regulating these facilities.

7.2.2 Selection of Numerical Limits

Our evaluations of waste management operations indicate that population doses are relatively small and that limiting doses to individuals is the optimal method to control radionuclide releases. Estimated releases are small enough that they conform to the 25 mrem/year limit established in 40 CFR 190.

Our estimates show that the highest individual doses for the waste management operations preparatory to terrestrial disposal of either spent fuel or reprocessed wastes are about 15 to 20 millirem per year at a rural site and about 135 millirem per year at an urban site. These maximum doses are caused by the solidification of 1-year-old liquid wastes. The highest individual doses have not been estimated for operations serving extraterrestrial waste disposal and transmutation. These operations are similar to some of the operations in the Uranium Fuel Cycle and are, therefore, expected to have similar doses.

Dose Limits Higher than those in 40 CFR 190

Setting permissible dose limits higher than those in 40 CFR 190 (e.g., a level of 250 millirem per year) would accomodate the doses estimated for solidification at an urban site and would allow latitude for other operations. We do not believe, however, that there is justification for setting limits above those established by 40 CFR 190. Our investigations indicate that there is no need for latitude in dose limitations for any operations other than solidification. We estimate that only a few solidification facilities will be required to carry out the waste management program and that most of these are expected to be operated in conjunction with fuel reprocessing. Since fuel reprocessing requires large exclusion areas, we see little or no problem with restricting waste solidification to rural sites.

Therefore we reject dose limits higher than those in 40 CFR 190.

Dose Limits Lower than those in 40 CFR 190

Our assessment is that the waste management operations required for terrestrial disposal could be carried out with annual dose limits to the maximally exposed individual below those required by 40 CFR 190. The principal requirement is that extended storage (for periods greater than 1 year) be provided before solidification of reprocessed wastes. There is insufficient information to establish that the operations in support of extraterrestrial disposal or transmutation could meet 40 CFR 190.

In the environmental impact statement for the 40 CFR 190 standards (EPA 76), we considered the alternatives of reducing the annual whole-body dose limits from 25 millirem to 15 millirem, then to 5 millirem, with comparable reductions of permissible dose limits to thyroid and other organs. We judged the improvements to be "not significant" and "small" respectively. The improvements in public health from dose limits below 25 millirem for waste management operations would be even smaller and would affect a smaller industry.

Implementation of standards with lower limits than those in 40 CFR 190 would be difficult. Doses could be estimated by establishing environmental transport models for measured effluent releases, but confirmation of doses by direct measurement of environmental concentrations of nuclides would be at or beyond the state of the art for environmental monitoring.

Establishment of dose limits substantially more restrictive than the 40 CFR 190 limits might preclude operations supporting extraterrestrial disposal and transmutation. Environmental protection must include all parts of the management and disposal of spent fuel and high-level and transuranic wastes. The possible benefits that might result from further investigation of extraterrestrial disposal and transmutation outweigh the small benefits of reducing the limits for the operational standards. The Interagency Review Group has recommended further research on extraterrestrial disposal options (IRG 79).

We reject dose limitation standards below those of 40 CFR 190, because they would not provide significant reductions in risk. They would be more difficult to implement, and they would preclude consideration of other potentially useful technologies.

Limits Equal to those of 40 CFR 190

As discussed in section 7.2.1, administration of the individual dose limits for the waste management operations standard is simplified if its format is the same as that for the Uranium Fuel Cycle standards. There is, in our judgment, no justification for setting the individual dose limits above those established by 40 CFR 190. There is little to be gained in setting the limit lower than 40 CFR 190. Therefore, we have chosen individual dose limits equal to those of 40 CFR 190 as the proposed standard.

The proposed standard establishes limits of 25 millirem per year to the whole body, 75 millirem per year to the thyroid, and 25 millirem to any other organ of any member of the general population. These limits are known to be readily implementable, are protective of the public, and do not impose prohibitive costs. These dose limits would permit the use of available monitoring capabilities and would require the use of the best available technology to prevent excessive radiation exposure of the public. We estimate that these limits would not preclude extraterrestrial disposal or transmutation.

7.2.3 Implications of the Operational Standards

The proposed waste management operations standards extend the protection of 40 CFR 190 to similar activities not included under that regulation. With the exception of transportation, generally applicable environmental standards will apply to all operations in the generation of commercial electrical power, from milling of uranium ore through emplacement of wastes in their final disposal site.

The proposed standards provide that doses to individuals from combined operations covered by 40 CFR 190 and 40 CFR 191 shall not exceed the limits of either part. This provision is analagous to the provision that the dose limits for any individual from any combination of the activities covered by 40 CFR 190 shall be the same as those from any single activity. Together, the two standards prevent an individual from receiving excessive doses from any combination of nuclear activities.

Chapter 8

ENVIRONMENTAL IMPACTS

Our proposed standards address the operations required to store, prepare, and dispose of high-level and transuranic wastes, as well as the long-term performance of their disposal systems over 10,000 years. The intent of these standards is to minimize releases of radionuclides to the environment and to assure that the risks to the public health and safety are small.

8.1 HEALTH IMPACT

8.1.1 Standards for Waste Management Operations

The proposed standards for waste management operations limit the maximum dose to an individual in the general population to 25 millirem per year. Evaluations of emissions from existing facilities indicate that actual doses can be expected to be much lower than 25 millirem per year, and will generally range between 5 and 10 millirem per year. However, the possible proximity of waste management facilities to other operations of the uranium fuel cycle already governed by a limit of 25 millirem per year under 40 CFR 190--and the difficulty of measuring such small emissions--make it impractical to impose a smaller limit. In addition, we do not want to preclude development of alternative disposal methods that, while they may lead to slightly larger doses to some people during the operational phase, could lead to a significantly lower long-term risk to

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future generations. The overall risk to populations, as opposed to the risk to individuals, from releases from management operations for high-level and transuranic waste disposal is expected to be small, because we anticipate that only a few such facilities will be needed to process both existing and future inventories. Thus, we conclude that the risk to both individuals and to populations from management operations for high-level waste disposal carried out according to these standards will be small and will present no significant hazard to the public health and welfare.

8.1.2 Disposal

The proposed standards for disposal set limits for releases of specific radionuclides over the first 10,000 years after disposal. The maximum impact expected over this time period from disposal in compliance with these containment requirements is estimated to be about 10 excess premature deaths from cancer for each 1000 metric tons of heavy metal (MTHM) charged to the reactor. In making this estimate, we have used an approach we believe makes the estimates conservatively large.

We expect that the first method to be utilized for disposal of high-level radioactive and transuranic wastes will be disposal in a mined repository deep in a continental rock formation. To obtain a basis for judging whether such disposal will meet our standards, we have made risk assessments for a model repository in different geologic media. The model repository is similar to current concepts of repositories discussed in recent literature. The model assumes release of radionuclides might occur by any of several modes after disposal in the repository. The radionuclides considered are those that our evaluation indicates have a potential to make a significant contribution to the total exposure expected from the release of a fraction of the radioactive waste. Our estimates show about 700 expected health effects from a repository in granite and about 100 from a repository in bedded salt over 10,000 years. We judge this impact to be small.

8.2 CONTAMINATION OF THE ENVIRONMENT

The limits that the standards for disposal set for releases to the accessible environment generally prevent contamination of any part of that environment to a level that would interfere with its use. We made the health impact estimates discussed in section 8.1.2 on the assumption that the accessible environment was used without restriction once 100 years had passed after disposal.

The standards for disposal do not, however, limit releases to sources of groundwater within 10 kilometers from the emplacement of these radioactive wastes. Our assessment of individual doses has shown that inadvertant human intrusions for resource exploration could significantly contaminate groundwater areas of a few tens of thousands of square meters. More serious contamination could occur as a result of severe, improbable natural events such as faulting.

However, the standards for disposal do tend to restrict the nature of the sources of groundwater that could be contaminated. Because the standards impose limits on the amounts of radioactive nuclides that can reach groundwater more than 10 kilometers from the point of emplacement of wastes, any unprotected groundwater must move very slowly. Slowly moving groundwater is usually contained in relatively impermeable formations that are poor producers of water and, therefore, are unlikely to be exploited. Although a certain amount of groundwater may become contaminated--and lost for potential future use--we believe that this minor resource loss would be justified by the very good long-term protection that would be provided by disposal systems complying with our standards.

8.3 CONCLUSION

The proposed standards for waste management operations limit doses to persons in the general population to 25 mrem/year. In actual practice, few people are expected to be exposed, and doses are expected to be substantially below this limit. Therefore, we conclude that these waste management operations do not represent a significant risk to the health and safety of the population.

The maximum impact expected from a disposal system in compliance with this standard is estimated to be less than 1,000 premature cancer deaths over the first 10,000 years for disposal of the high-level wastes from 100,000 MTHM of reactor fuel (about as much as all currently operating reactors should produce over their lifetimes). The environmental impacts of the alternatives we considered range up to about 10 times as large as this; these impacts are discussed in Chapter 4. Our analyses indicate that construction of repositories in bedded salt or granite can achieve our proposed containment requirements, and repositories in other geologic media may as well. Comparison with other environmental radiation hazards indicates that disposal in compliance with our proposed standards would represent a very small added risk to the population over such an extended period of time.

Chapter 9

REGULATORY IMPACT

This chapter reviews the projected costs associated with management and disposal of high-level radioactive waste, and it summarizes the potential regulatory impacts of our proposed standards. The details of the analyses described here are presented in our Regulatory Impact Analysis (EPA 82), prepared in accordance with Executive Order 12291.

The situation regarding the disposal of high-level waste is unusual from a regulatory standpoint. In most cases, a regulation concerns an ongoing activity. Any modifications that the regulation causes in the activity may be considered to be costs that should be outweighed by the regulatory benefits. For high-level waste disposal, however, the appropriate regulations must be developed well before the activity to be regulated can even begin. Thus, the typical perspectives about balancing regulatory costs and benefits do not apply.

To investigate the potential impacts of this proposed action, we evaluated how the costs of high-level waste management and disposal might change due to alternative stringency levels of our containment requirements--or due to changes in our assurance requirements. Because there is no "baseline" program to consider, we could not quantify the costs and benefits of our proposed action compared to the consequences of no regulation.

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The most important benefit of our action should be the assurance that these wastes will be disposed of with adequate protection of public health and the environment. This assurance, in turn, should allow the Federal program to proceed expeditiously to develop acceptable disposal methods at appropriate sites. It may be argued that a further benefit would be the resolution of a key issue that might lead to expanded commercial use of nuclear power. This would be a benefit if nuclear power has clear advantages, economic and otherwise, compared to alternative methods of generating electricity; however, we have not analyzed this issue.

Our containment requirements consist of limits on potential releases of radioactivity from a disposal system; these limits are to be used as overall design objectives. These requirements are stated in terms of projected releases for 10,000 years after disposal of the wastes. To judge the risks associated with these release limits, we have used generalized environmental pathway models to assess the potential health impacts of the releases that would be allowed by our standards. However, calculations of these "residual risks" are clearly not reliable as absolute values, since projections of population distributions, ways of life, and human behavior over 10,000 years cannot be meaningful. Rather, these calculations are valuable only for understanding the relative "residual risks" from different sources of radiation exposure (such as risks from different disposal system designs, or risks from natural ore bodies).

For the release limits we have proposed as part of our environmental standards, the residual risks projected by these models would be less than 1,000 premature deaths from cancer over the 10,000 year period, an average of one premature death every 10 years. To judge the effects on disposal costs of changing the level of protection, we also compared release limits corresponding to residual risk values of: 100, 1,000, 5,000, and 10,000 premature deaths over the 10,000 year period. We chose this range of residual risks because it appears to represent the range of performance that may be expected of mined geologic repositories.

To do this analysis, we evaluated the long-term performance of generic models of geologic repositories in three different geologic media: bedded salt, granite, and basalt. We did the analysis in two steps:

First, we used our performance projections to assess the quality of the engineering controls that would be needed in each of the three model repositories to meet each of the four different levels of protection. In doing so, we encountered the problem that development of specific engineered barriers (e.g., waste forms and canisters) has not yet progressed enough to clearly associate the costs of manufacturing these engineered barriers with their performance levels. Thus, we had to make some rather speculative judgments to associate disposal costs with alternative stringency levels. The results of this analysis are displayed in Figure 9-1.

(Engineering Barrier Costs Only)

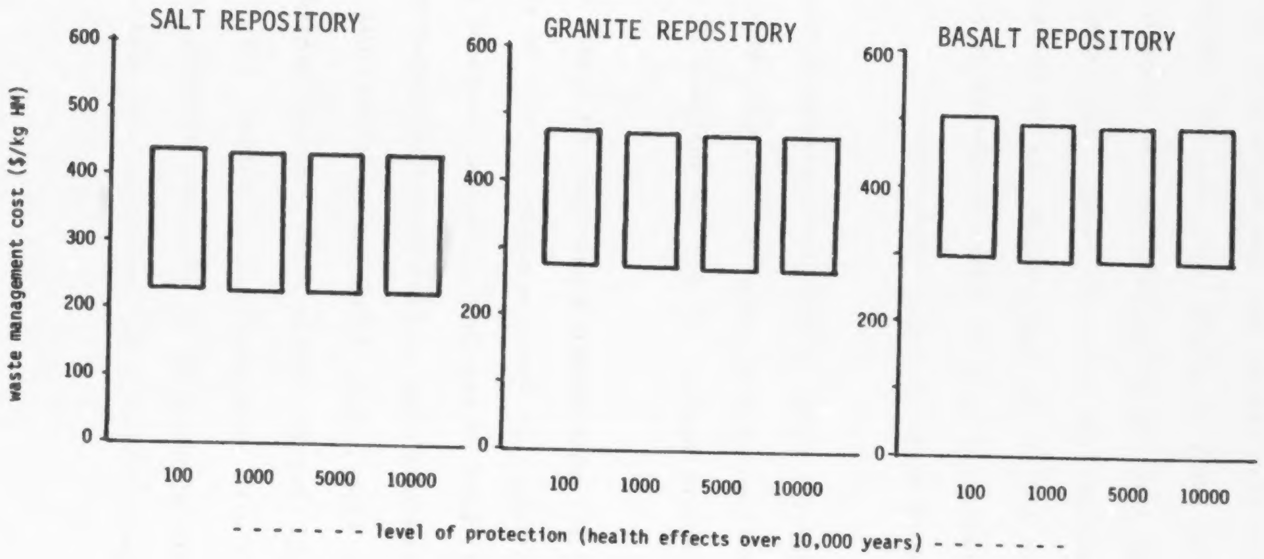

FIGURE 9-1: VARIATIONS IN WASTE MANAGEMENT COST vs. LEVEL OF PROTECTION

Second, we tried to allow for the possible effect of alternative stringency levels on site selection. This is particularly relevant because our analyses indicate that the most important part of the protection offered by a mined geologic repository comes from the hydrological and geochemical characteristics of the site itself. The costs of using a "good" site rather than a "bad" site (within the same type of geologic media) do not involve differences in construction cost. Instead, they involve the difficulty of finding a site that is "good enough." Since there are so few data on site characterization, we have no good basis for judging how many sites might have to be studied to meet different levels. However, we did made some assumptions about how site selection costs might increase in order to meet more stringent standards. We then combined these assumptions with our evaluations of the variations in engineered barrier costs to arrive at our second set of disposal cost estimates. The results from this analysis are shown in Figure 9-2.

The results of these assessments of disposal costs and alternative stringency levels indicate that the costs are not very sensitive to different levels of protection, particularly for the geologic media (bedded salt and granite) that are better at reducing long-term risks. Even with our hypothesis about increased site selection costs with more stringent levels, the difference in costs for different levels are much smaller than the overall uncertainties in waste management costs. For example, consider the increased costs of complying with the release limits we have proposed, rather than release limits 10 times less stringent.

(Engineering Barrier Costs and Site Selection Costs)

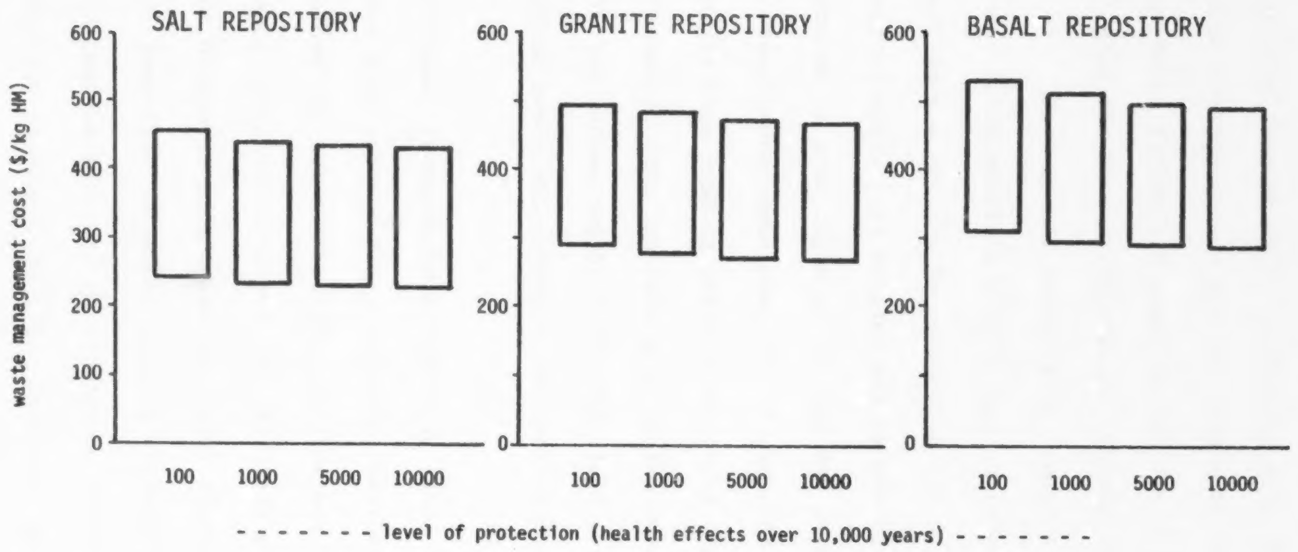

FIGURE 9-2: VARIATIONS IN WASTE MANAGEMENT COST vs. LEVEL OF PROTECTION

The potential increase ranges from zero to 50 million (1981) dollars per year. For comparison, the total costs of high-level waste management and disposal (independent of our action) have been estimated as between 700 million and almost 1.5 billion (1981) dollars per year. Electrical utility revenues were about 100 billion dollars in 1980.

These analyses, while indicating that disposal costs appear to be relatively insensitive to differences in the level of protection, do not provide a way to determine the acceptability of the residual risks from a societal perspective, nor do they indicate a level of protection that is preferable from a balancing of costs and benefits. One possible approach to balancing costs and benefits would be to judge the cost per life saved by different levels of protection, perhaps taking into account some method of discounting costs and benefits. However, our calculations of residual risks are not reliable as absolute values. Thus, we have no meaningful way to calculate an absolute value of the cost per life saved by different levels of protection.

In the absence of the ability to make meaningful cost and benefit comparisons, we have used other tests of economic feasibility and acceptability of risk to judge the appropriateness of the level of protection we have proposed. As discussed above, setting the release limits at the level we chose--as opposed to a level 10 times less or 10 times more stringent--appears to cause only very minor effects on the costs of high-level waste disposal. To judge the acceptability of the remaining long-term risk, we considered the risks that would otherwise be caused if the uranium ore used to produce the wastes had not been mined. The magnitude of the risks from these unmined ore bodies is very uncertain due, in part, to the wide variety of settings in which uranium ore is found--many of which are closer to the surface than a geologic repository would be. Using the same generalized environmental pathway models that were used to assess the risks from our models of geologic repositories, the risks from a comparable amount of unmined uranium ore are estimated to range from a few hundred to more than 1 million health effects over 10,000 years (WI 80). The lower end of this range is roughly equal to the residual risk associated with our proposed release limits. Thus, the upper limit of the risk that our standards would allow from the disposal of high-level wastes appears to pose a threat very close to the minimal risk posed by nature, had the uranium ore never been mined and the high-level wastes never been generated.

Our assurance requirements provide seven qualitative criteria that should reduce some of the uncertainties inherent in disposing of wastes that must be isolated for a very long time. The specific provisions of these assurance requirements are described in Chapter 6 of this document. Only three of the criteria have a significant potential to increase the costs of high-level waste disposal. These are:

> Criterion 2, which calls for disposal systems to keep radioactive releases as small as reasonably achievable;
>
> Criterion 3, which calls for disposal systems to use multiple barriers, both engineered and natural; and
>
> Criterion 4, which restricts reliance on active institutional controls to a resonable period after disposal (e.g., a few hundred years).

Each of these three assurance requirements might have the effect of requiring better engineered barriers than would otherwise be needed to meet our environmental standards. This would be particularly true for a repository sited in a relatively good geologic media (such as our generic models for bedded salt or granite). However, even if no engineered barriers at all appeared to be needed for long-term protection after disposal, fairly protective canisters and waste forms would be needed for other phases of waste management, such as transportation to and emplacement in a repository. Therefore, we believe that these assurance requirements would necessitate--at most--only moderate improvements in waste form performance, and we judged that the impact that these improvements might have on disposal costs should be less than 10 million (1981) dollars per year. Since this impact concerns improvements to engineered barriers, the potential cost increase would be duplicative of any engineered barrier impacts caused by our environmental standards. Thus, the potential cost effects of our containment requirements and our assurance requirements should generally not be added together. (For some unusual possibilities, adding the effects of the containment requirements and the assurance requirements might be appropriate, but these possibilities would tend to involve relatively small impacts.)

Appendix A

THE PROPOSED STANDARDS

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A new Part 191 is proposed to be added to Title 40, Code of Federal Regulations, as follows:

SUBCHAPTER F - RADIATION PROTECTION PROGRAMS

PART 191 - ENVIRONMENTAL RADIATION PROTECTION STANDARDS FOR MANAGEMENT AND DISPOSAL OF SPENT NUCLEAR FUEL, HIGH-LEVEL AND TRANSURANIC RADIOACTIVE WASTES

Subpart A - Environmental Standards for Management and Storage

191.01 Applicability

191.02 Definitions

191.03 Standards for Normal Operations

191.04 Variances for Unusual Operations

191.05 Effective Date

Subpart B - Environmental Standards for Disposal

191.11 Applicability

191.12 Definitions

191.13 Containment Requirements

191.14 Assurance Requirements

191.15 Procedural Requirements

191.16 Effective Date

AUTHORITY: The Atomic Energy Act of 1954, as amended; Reorganization Plan No. 3 of 1970.

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SUBPART A - ENVIRONMENTAL STANDARDS FOR MANAGEMENT AND STORAGE

191.01 Applicability

This Subpart applies to radiation doses received by members of the public as a result of the management (except for transportation) and storage of spent nuclear fuel, high-level, or transuranic radioactive wastes, to the extent that these operations are not subject to the provisions of Part 190 of Title 40.

191.02 Definitions

Unless otherwise indicated in this Subpart, all terms shall have the same meaning as in Subpart A of Part 190.

(a) "Spent nuclear fuel" means any nuclear fuel removed from a nuclear reactor after it has been irradiated.

(b) "High-level radioactive wastes" means any of the following that contain radionuclides in concentrations greater than those identified in Table 1: (1) liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, in a facility for reprocessing spent nuclear fuels; (2) the concentrated wastes from subsequent extraction cycles, or equivalent; (3) solids into which such liquid wastes have been converted; or (4) spent nuclear fuel if disposed of without reprocessing.

(c) "Transuranic wastes," as used in this Part, means wastes containing more than 100 nanocuries of alpha emitting transuranic isotopes, with half-lives greater than one year, per gram of waste.

(d) "Storage" means placement of radioactive wastes with planned capability to readily retrieve such materials.

(e) "Management and storage" means any activity, operation, or process, except for transportation, conducted to prepare spent nuclear fuel, high-level or transuranic radioactive wastes for storage or disposal, the storage of any of these materials, or activities associated with the disposal of these materials.

(f) "General environment" means the total terrestial, atmospheric, and aquatic environments outside sites within which any operation associated with the management and storage of spent nuclear fuel, high-level or transuranic radioactive wastes is conducted.

(g) "Member of the public" means any individual who is not engaged in operations involving the management, storage, and disposal of materials covered by these standards. A worker so engaged is a member of the public except when on duty at a site.

191.03 Standards for Normal Operations

Operations covered by this Subpart should be conducted so as to reduce exposures to members of the public to the extent reasonably achievable, taking into account technical, social, and economic considerations. As an upper limit, except for variances in accordance with 191.04, these operations shall be conducted in such a manner as to provide reasonable assurance that the combined annual dose equivalent to any member of the public due to: (a) operations covered by Part 190,

(b) planned discharges of radioactive material to the general environment from operations covered by this Subpart, and (c) direct radiation from these operations; shall not exceed 25 millirems to the whole body, 75 millirems to the thyroid, or 25 millirems to any other organ.

191.04 Variances for Unusual Operations

(a) The implementing agency may grant a variance temporarily authorizing operations which exceed the standards specified in 191.03 when abnormal operating conditions exist if: (1) a written request justifiying continued operation has been submitted, (2) the costs and benefits of continued operation have been considered to the extent possible, (3) the alternatives to continued operation have been considered, and (4) continued operation is deemed to be in the public interest.

(b) Before the variance is granted, the implementing agency shall announce, by publication in the Federal Register and by letter to the governors of affected States: (1) the nature of the abnormal operating conditions, (2) the degree to which continued operation is expected to result in doses exceeding the standards, (3) the proposed schedule for achieving conformance with the standards, and (4) the action planned by the implementing agency.

191.05 Effective Date

The standards in this Subpart shall be effective 12 months from the promulgation date of this rule.

SUBPART B - ENVIRONMENTAL STANDARDS FOR DISPOSAL

191.11 Applicability

This Subpart applies to radioactive materials released into the accessible environment as a result of the disposal of high-level or transuranic radioactive wastes, including the disposal of spent nuclear fuel. This Subpart does not apply to disposal directly into the oceans or ocean sediments.

191.12 Definitions

Unless otherwise indicated in this Subpart, all terms shall have the same meaning as in Subpart A of this Part.

(a) "Disposal" means isolation of radioactive wastes with no intent to recover them.

(b) "Barriers" means any materials or structures that prevent or substantially delay movement of the radioactive wastes toward the accessible environment.

(c) "Disposal system" means any combination of engineered and natural barriers that contains radioactive wastes after disposal.

(d) "Groundwater" means water below the land surface in a zone of saturation.

(e) "Lithosphere" means the solid part of the Earth, including any groundwater contained within it.

(f) "Accessible environment" includes (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) parts of the lithosphere that are more than ten kilometers in any direction from the original location of any of the radioactive wastes in a disposal system.

(g) "Reasonably foreseeable releases" means releases of radioactive wastes to the accessible environment that are estimated to have more than one chance in 100 of occurring within 10,000 years.

(h) "Very unlikely releases" means releases of radioactive wastes to the accessible environment that are estimated to have between one chance in 100 and one chance in 10,000 of occurring within 10,000 years.

(i) "Performance assessment" means an analysis which identifies those events and processes which might affect the disposal system, examines their effects upon its barriers, and estimates the probabilities and consequences of the events. The analysis need not evaluate risks from all identified events. However, it should provide a reasonable expectation that the risks from events not evaluated are small in comparison to the risks which are estimated in the analysis.

(j) "Active institutional controls" means (1) guarding a disposal site, (2) performing maintenance operations or remedial actions at a disposal site, or (3) controlling or cleaning up releases from a disposal site.

(k) "Passive institutional controls" means (1) permanent markers placed at a disposal site, (2) public records or archives, (3) Federal Government ownership or control of land use, or (4) other methods of preserving knowledge about the location, design, or contents of a disposal system.

(l) "Heavy metal" means all uranium, plutonium, or thorium placed into a nuclear reactor.

191.13 Containment Requirements

Disposal systems for high-level or transuranic wastes shall be designed to provide a reasonable expectation that for 10,000 years after disposal:

(a) Reasonably foreseeable releases of waste to the accessible environment are projected to be less than the quantities calculated according to Table 2.

(b) Very unlikely releases of waste to the accessible environment are projected to be less than ten times the quantities calculated according to Table 2.

191.14 Assurance Requirements

To provide the confidence needed for compliance with the containment requirements of 191.13, disposal of high-level or transuranic wastes shall be conducted in accordance with the following requirements:

(a) Wastes shall be disposed of promptly once disposal systems are available and the wastes have been suitably conditioned for disposal.

(b) Disposal systems shall be selected and designed to keep releases to the accessible environment as small as reasonably achievable, taking into account technical, social, and economic considerations.

(c) Disposal systems shall use several different types of barriers to isolate the wastes from the accessible environment. Both engineered and natural barriers shall be included. Each such barrier shall separately be designed to provide substantial isolation.

(d) Disposal systems shall not rely upon active institutional controls to isolate the wastes beyond a reasonable period of time (e.g., a few hundred years) after disposal of the wastes.

(e) Disposal systems shall be identified by the most permanent markers and records practicable to indicate the dangers of the wastes and their location.

(f) Disposal systems shall not be located where there has been mining for resources or where there is a reasonable expectation of exploration for scarce or easily accessible resources in the future. Furthermore, disposal systems shall not be located where there is a significant concentration of any material which is not widely available from other sources.

(g) Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.

191.15 Procedural Requirements

Performance assessments to determine compliance with the containment requirements of 191.13 shall be conducted in accordance with the following:

(a) The assessments shall consider realistic projections of the protection provided by all of the engineered and natural barriers of a disposal system.

(b) The assessments shall not assume that active institutional controls can prevent or reduce releases to the accessible environment beyond a reasonable period (e.g., a few hundred years) after disposal. However, it should be assumed that the Federal Government is committed to retaining passive institutional control of disposal sites in perpetuity. Such passive controls should be effective in deterring systematic or persistent exploitation of a disposal site, and it should be assumed that they can keep the chance of inadvertent human intrusion very small as long as the Federal Government retains such passive control of disposal sites.

(c) The assessments shall use information regarding the likelihood of human intrusion, and all other unplanned events that may cause releases to the accessible environment, as determined by the implementing agency for each particular disposal site.

191.16 Effective Date

The standards in this Subpart shall be effective immediately upon promulgation of this rule; however, this Subpart does not apply to wastes disposed of before promulgation of this rule.

TABLE 1 - CONCENTRATIONS IDENTIFYING HIGH-LEVEL RADIOACTIVE WASTES

Radionuclide	Concentration (curies per gram of waste)
Carbon-14	8×10^{-6}
Cesium-135	8×10^{-4}
Cesium-137	5×10^{-3}
Plutonium-241	3×10^{-6}
Strontium-90	7×10^{-3}
Technetium-99	3×10^{-6}
Tin-126	7×10^{-7}
Any alpha-emitting transuranic radionuclide with a half-life greater than 20 years	1×10^{-7}
Any other radionuclide with a half-life greater than 20 years	1×10^{-3}

NOTE: In cases where a waste contains a mixture of radionuclides, it shall be considered a high-level radioactive waste if the sum of the ratios of the radionuclide concentration in the waste to the concentration in Table 1 exceeds one.

For example, if a waste containing radionuclides A, B, and C in concentrations C_a, C_b, and C_c, and if the concentration limits from Table 1 are CL_a, CL_b, and CL_c, then the waste shall be considered high-level radioactive waste if the following relationship exists:

$$\frac{C_a}{CL_a} + \frac{C_b}{CL_b} + \frac{C_c}{CL_c} \geqslant 1$$

TABLE 2 - RELEASE LIMITS FOR CONTAINMENT REQUIREMENTS

(Cumulative Releases to the Accessible Environment
for 10,000 Years After Disposal)

Radionuclide	Release Limit (curies per 1000 MTHM)
Americium-241	10
Americium-243	4
Carbon-14	200
Cesium-135	2000
Cesium-137	500
Neptunium-237	20
Plutonium-238	400
Plutonium-239	100
Plutonium-240	100
Plutonium-242	100
Radium-226	3
Strontium-90	80
Technetium-99	10000
Tin-126	80
Any other alpha-emitting radionuclide	10
Any other radionuclide which does not emit alpha particles	500

NOTE 1: The Release Limits in Table 2 apply either to the amount of high-level wastes generated from 1,000 metric tons of heavy metal (MTHM), or to an amount of transuranic (TRU) wastes containing one million curies of alpha-emitting transuranic radionuclides. To develop Release Limits for a particular disposal system, the quantities in Table 2 shall be adjusted for the amount of wastes included in the disposal system. For example:

(a) If a particular disposal system contained the high-level wastes from 50,000 MTHM, the Release Limits for that system would be the quantities in Table 2 multiplied by 50 (50,000 MTHM divided by 1,000 MTHM).

(b) If a particular disposal system contained five million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table 2 multiplied by five (five million curies divided by one million curies).

(c) If a particular disposal system contained both the high-level wastes from 50,000 MTHM and 5 million curies of alpha-emitting transuranic wastes, the Release Limits for that system would be the quantities in Table 2 multiplied by 55:

$$\frac{50{,}000\ \text{MTHM}}{1{,}000\ \text{MTHM}} + \frac{5{,}000{,}000\ \text{curies TRU}}{1{,}000{,}000\ \text{curies TRU}} = 55$$

NOTE 2: In cases where a mixture of radionuclides is projected to be released, the limiting values shall be determined as follows: For each radionuclide in the mixture, determine the ratio between the cumulative release quantity projected over 10,000 years and the limit for that radionuclide as determined from Table 2 and Note 1. The sum of such ratios for all the radionuclides in the mixture may not exceed one.

For example, if radionuclides A, B, and C are projected to be released in amounts Q_a, Q_b, and Q_c, and if the applicable Release Limits are RL_a, RL_b, and RL_c, then the cumulative releases over 10,000 years shall be limited so that the following relationship exists:

$$\frac{Q_a}{RL_a} + \frac{Q_b}{RL_b} + \frac{Q_c}{RL_c} \leq 1$$

Appendix B

RISK ASSESSMENTS OF GEOLOGIC REPOSITORIES

Our assessments of the health risks associated with disposal in mined geologic repositories are intended to provide conservative estimates of the potential risks from our model repository systems. (The repository characteristics were chosen to be stringent enough for adequate protection, but lenient enough to be reasonably achievable.) More sophisticated risk assessments of these model repositories--using more realistic repository performance characteristics--should predict less harm than our estimates. Some potential repository sites should be more environmentally acceptable than our models; others could be less environmentally acceptable. The Department of Energy and the Nuclear Regulatory Commission will perform assessments of specific candidate repository sites.

Our risk assessments include estimates of the potential harm to a representative population and estimates of the annual dose equivalents to highly exposed individuals. We chose to express the harm to the population as numbers of fatal cancers and numbers of genetic effects--and the individual dose assessments in annual dose equivalent--rather than as the quantities or concentrations of radioactive materials released to the environment. This approach allows us to combine the effects of the various radionuclides and to represent more clearly the potential risks of high-level waste disposal.

By varying the hypothetical conditions of our generic model repositories, we can explore a wide variety of circumstances. These projections then become a tool for comparing various conditions as they

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affect repository performance. Some postulated conditions may produce risks too high to be considered acceptable; others may greatly reduce the risks but may be technologically or economically unattainable. The full report of our population risk assessment and our individual dose assessment are presented in Smith, et al. (SMC 82) and Goldin, et al. (GO 82), respectively.

B.1 GENERAL FEATURES OF THE MODEL

The model system used for our assessment is made up of five parts:

1. the waste container;
2. the physical and chemical characteristics of the waste itself (the waste form);
3. the geologic medium into which the waste is placed (the host rock);
4. the geologic media between the host rock and man's environment (the geosphere);
5. the environmental (i.e., above ground) pathways through which people can come into contact with waste radionuclides (the biosphere).

The first four parts are characteristics of the disposal system and are common to both the population and the individual risk assessments; the fifth part, while considered in both assessments, is treated differently because of the different approaches needed to assess individual and population exposures. These environmental pathways are discussed more completely by Smith, Fowler, and Goldin (SMJ 82). The events and processes leading to radionuclide releases are discussed in section B.2, together with the population risk assessments. The individual dose assessments are presented in section B.3.

B.1.1 Waste Characteristics

Table B-1 lists the major radionuclides contained in the radioactive inventory of our model repository. We selected these 15 radionuclides on the basis of their quantity in spent fuel, their half-lives, and their biological behavior as reflected in dose-equivalent conversion factors (rem per curie ingested or inhaled). Table B-2 lists the geochemical characteristics (i.e., retardation factors and solubility limits) of each of these radionuclides.

Each model repository contains the waste from 100,000 metric tons of heavy metal (MTHM) charged to reactors. We assume the waste is in the form of unreprocessed spent fuel, since this assumption requires examination of the behavior of both the fission products and the transuranic nuclides. The composition by weight of the spent fuel is assumed to be 95.5 percent uranium isotopes, 0.9 percent plutonium isotopes, 0.1 percent other transuranic isotopes, and 3.5 percent fission products. We assume all the spent fuel has aged for approximately 10 years after discharge from the reactors. More detailed information on the repository inventory is given by Arthur D. Little, Inc. (ADL 79).

Continued integrity of the waste containers assures retention of the radioactive wastes in the repository. If the containers fail, release of the radioactive material depends on either the release rate of nuclides from the fuel matrix (waste form) or the solubility of the radioactive elements as they come into contact with the groundwater. For our

Table B-1

Characteristics of Radioactive Waste

(Spent Fuel)

Radionuclide	Initial Quantity in Repository (ADL 79) (curies)	Half-Life (years)
Pu-238	220,000,000	89
Pu-239	33,000,000	24,400
Pu-240	49,000,000	6,260
Pu-242	170,000	380,000
Am-241	17,000,000	458
Am-243	1,700,000	7,650
Np-237	33,000	2,140,000
Cs-135	22,000	3,000,000
Cs-137	8,600,000,000	30
I-129	3,800	16,000,000
Tc- 99	1,400,000	210,000
Sn-126	56,000	100,000
Zr- 93	190,000	950,000
Sr- 90	6,000,000,000	29
C- 14	28,000	5,730

Table B-2

Solubility Limits and Retardation Factors (SMC 82)

Radionuclide	Solubility Limit		Retardation Factor
	(Ci/m^3)	(ppm)	
Pu-239	6.0E-5	0.001	100
Pu-240	2.2E-4	0.001	100
Pu-242	4.0E-6	0.001	100
Am-241	160	50.0	100
Am-243	10	50.0	100
Np-237	7.2E-7	0.001	100
Cs-135	na	na	1
Cs-137	na	na	1
I-129	na	na	1
Tc- 99	2.0E-5	0.001	1
Sn-126	3.0E-2	1.0	10
Zr- 93	na	na	1
Sr- 90	na	na	1
C- 14	na	na	1

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na = Solubility limit not used or not known

ppm = parts radionuclide per million parts solution by weight.

reference cases, containers last 100 years in salt and 500 years in other media. For the release rate, we assume that, after failure of the container, a constant fraction of the remaining radionuclide dissolves per unit time in the repository groundwater. For our reference cases, this fraction is taken to be 1 part in 10,000 (10^{-4}) per year. The solubility limits become important when there is not enough water to dissolve the quantity of the radioactive element that could otherwise be released. This is usually the case for technetium, uranium, neptunium, and plutonium, and it also applies to americium in some situations.

B.1.2 Descriptions of Generic Repositories

Our population risk assessment report (SMC 82) and the Arthur D. Little study (ADL 79) describe our model repositories for five different geologic media--bedded salt, granite, basalt, shale, and salt dome. To demonstrate our analytical method, we will discuss only the bedded salt, granite, and basalt models, since, for our purposes, the model shale repository behaves very similarly to basalt and the salt dome repository behaves similarly to the bedded salt.

Each repository is 2 kilometers wide and 4 kilometers long. About one-fourth of the repository is mined for the waste, the rest being left as walls and pillars. The mined portion is 5 meters from floor to roof. After the wastes have been placed in the repository, the mined areas are backfilled. We assume that the backfill cannot be refilled to the original density, which results in void space amounting to 20 percent of its total volume, or 2,000,000 cubic meters.

The model bedded salt repository (Figure 5-1 on page 89) is 460 meters (1500 feet) below the surface. Above and below the repository layer are 50 meters of salt, 50 meters of impermeable rock, and a 30-meter thick, porous, water-bearing medium (aquifer). The characteristics of the overlying aquifer are shown in Table B-3. There are 330 meters of undefined sedimentary overburden between the top of the upper aquifer and the surface.

The granite repository (Figure 5-2 on page 90) is also modeled as 460 meters below the surface. The granite formation continues downward indefinitely, so there is no lower aquifer. There are 230 meters of granite above the repository and then an aquifer identical to the one modeled above the salt repository. Above the aquifer are 200 meters of overburden.

The basalt repository (Figure B-1) is also positioned at 460 meters underground, with 100 meters of basalt both above and below. The basalt is bounded by overlying and underlying 30-meter thick aquifers at 330 and 560 meters, respectively.

In granite and basalt, the void spaces in the backfill fill with groundwater moving from the aquifer through fractures in the bulk rock and also through the sealed shafts and boreholes. We assume that all the water becomes connected throughout the mined volume and shafts and can be considered as one large volume. In the salt repository, the water may

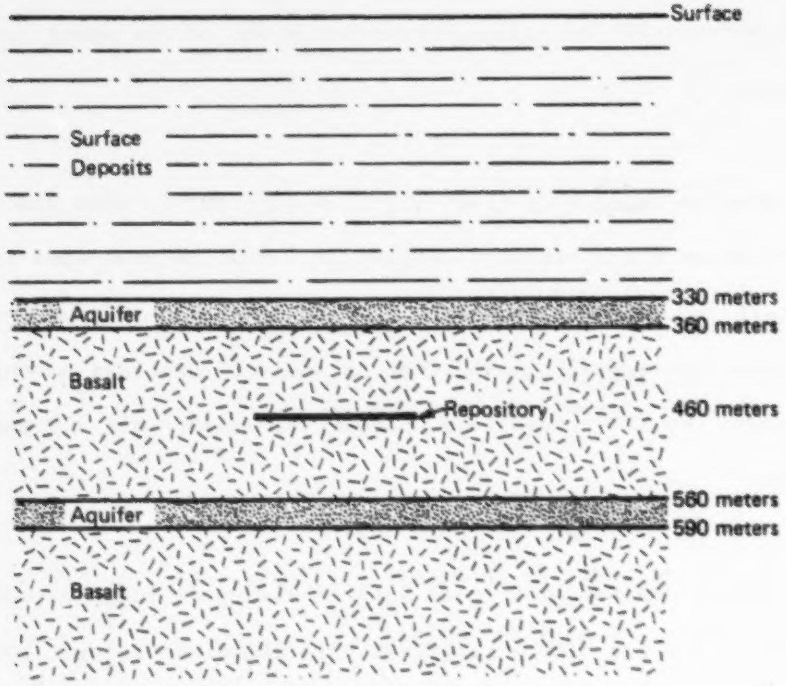
Surface
Surface Deposits
330 meters
Aquifer
360 meters
Basalt
Repository
460 meters
560 meters
Aquifer
590 meters
Basalt

FIGURE B-1: REFERENCE REPOSITORY IN BASALT

Table B-3

Aquifer Characteristics

Distance from repository to overlying aquifer (meters)	230.0 100.0 100.0	(granite) (bedded salt) (basalt)
Distance along aquifer to man's environment (meters)	1600.0	
Permeability in aquifer pathway (meters/year)	31.5	
Transverse diffusivity (meters)	6.0	
Gradient in aquifer pathway	0.01	
Effective porosity in aquifer pathway	0.15	
Thickness of aquifer (meters)	30.0	
Width of aquifer over repository (meters)	4000.0	

enter through imperfections in shaft and borehole seals. Once the salt repository has been closed, the salt begins to flow plastically under the weight of the overlying salt and the other geologic formations, so that most of the void space in the backfill is eliminated. Only a small amount of the water may remain trapped in the salt in the form of brine pockets. We assume that each brine pocket is in contact with two waste canisters and contains 0.06 cubic meters of brine.

B.2 RISK ASSESSMENTS FOR POPULATIONS

In this section we estimate the number of serious health effects (fatal cancers and genetic defects) that could result from releases of radionuclides from a repository. The three objectives of our analysis are: (1) to estimate the probabilities of accidental events, (2) to address the overall impact on man, and (3) to provide information for decision-making.

We considered mechanisms and initiating events that would release radionuclides from the model repository and their subsequent transport through the geosphere and the biosphere (SMC 82). Releases were categorized according to three general pathways to the biosphere: releases to air, releases to land surface, and releases to aquifers (and ultimately to surface water). A number of initiating events were then identified that would allow radionuclides to enter one or more of these media:

1. human intrusion (drilling for resources) -- releases to land surface and to aquifers
    a. direct hit on a canister
    b. intrusion into the repository without hitting a canister
2. faulting -- releases to aquifers
    a. destruction of canisters
    b. disturbance of repository without destroying canisters
3. breccia pipe formation -- releases to aquifers.
4. volcanoes -- releases to air and land surface
5. meteorite impact -- releases to air and land surface

For each repository type we examined a number of pathways in the biosphere through which people may be exposed to radiation. The pathways for releases to air were inhalation, eating contaminated foods, exposure to external radiation from contaminated air, and exposure to external radiation from contaminated land surface. The same pathways apply to releases to land surface since the nuclides deposited on land surface will be resuspended into the air. We also calculated the population risks from use of the streams into which the aquifers discharge. The pathways for releases to an aquifer and subsequent discharge from a stream are drinking water, eating fish, eating milk, meat, and irrigated foods, breathing air contaminated through resuspension, being exposured to external radiation from contaminated air, and being exposured to external radiation from contaminated land surfaces. We also calculated risks from eating seafood contaminated by entry of nuclides into the ocean from the rivers, but these risks were very small. We calculated the fraction of each nuclide ingested or inhaled by humans for each subpathway and then determined the resulting doses to each of 10 organs: ovaries, testes, red marrow, thyroid, lower gastrointestinal tract (LLI), lung, liver, kidney, bone, and total body (considered representative of other soft tissue). We used the dose equivalent conversion factors (rem per curie) of INREM-II (KI 78, DU 79) to calculate the organ doses. The ovary and testes doses were converted to genetic health effects, and the doses to the other organs were converted to fatal cancers. The genetic and fatal cancer dose-to-health effect conversion factors are based on the work of the BEIR Committee (NAS 72). For all the situations we considered, the number of potential genetic effects was always small relative to the projected number of fatal cancers; therefore, this discussion concentrates on the latter category of health effects.

B.2.1 Assessment Methodology

The consequences we assessed for a population are the number of fatal cancers produced by a release over the period of time considered. We examined the probability and consequences of each event occuring at a number of different times. The probabilities and consequences of all the possible events and event times can be combined in two ways. First, we can present the results in a graph in which the ordinate of a point on the graph gives the probability of obtaining at least the number of consequences shown on the abscissa. (For example, Figure B-2 illustrates total fatal cancers caused by releases from a granite repository in the first 10,000 years after repository sealing--it shows a probability greater than 1 in 10 of a few hundred fatal cancers in this time and less than a 1 in 100,000 probability of much more than a thousand fatal cancers.)

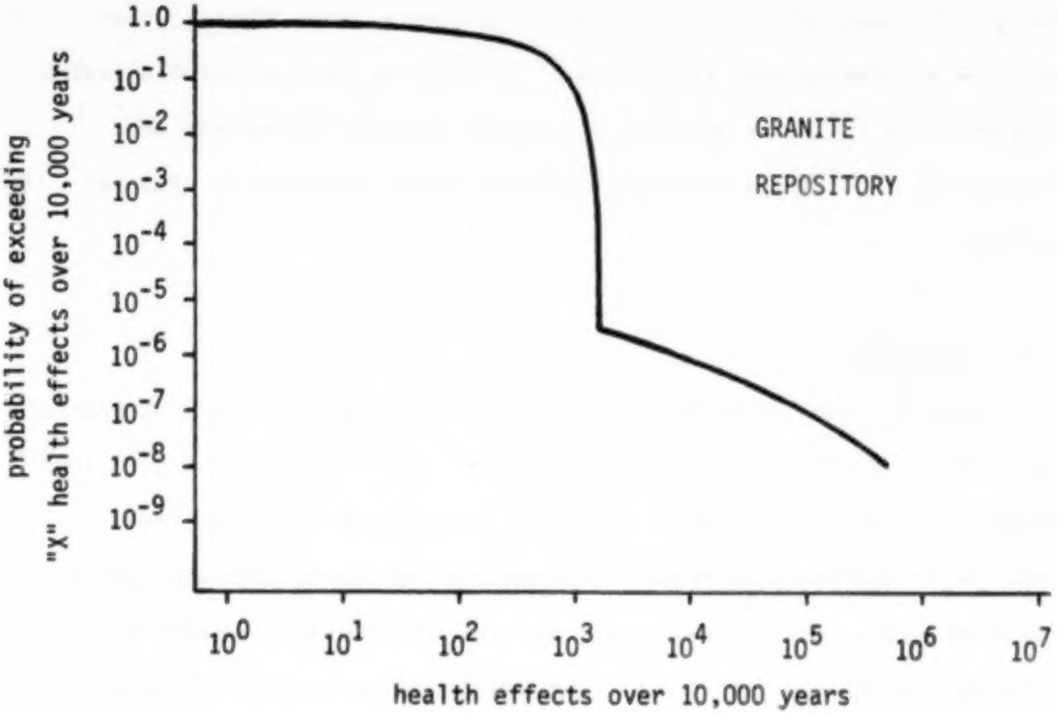

FIGURE B-2: PROBABILITY OF POPULATION RISKS OVER 10,000 YEARS

Alternatively, we can multiply each consequence by its probability and sum the products, obtaining an expected value for the total number of fatal cancers resulting from all events over the time period considered. (Figure 5-3 on page 99 displays the sums of the product of the probabilities and consequences for each type of event for the bedded salt and granite repositories--a total for each type of repository is then obtained by summing over all events.) In the remainder of our discussion of population risks, we will use the latter value to illustrate and compare the harm associated with different characteristics of disposal systems.

B.2.2 Releases

Table B-4 indicates the major repository characteristics that control the amount and rate of radionuclide release. Releases to air and to land surfaces are direct and rapid; the major controlling factor is the fraction of the waste affected. Releases through an aquifer are indirect and slow; the major controlling factors are the fraction of the waste affected and the rate of flow of contaminated water through the aquifer. The flow rate depends on the permeability, porosity, cross-sectional area of the flow path and the hydraulic gradient driving the flow. In the immediate vicinity of the repository, a major component in the hydraulic gradient is the buoyancy resulting from heat produced by the waste; any natural gradient between aquifers adds to the thermal buoyancy gradient. The maximum value of the thermal buoyancy gradient is about 0.25, which gradually decreases to zero as the waste cools (SMC 82). Table B-4 gives the particular characteristics associated with each of the release modes we analyzed.

Table B-4

Reference Case Characteristics (SMC 82)

	Granite	Bedded Salt	Basalt
Normal Groundwater Flow (to surface water via aquifer)			
Permeability of host rock (m/yr)	$3\text{x}10^{-4}$	--	$3\text{x}10^{-3}$
Porosity of host rock	$1\text{x}10^{-4}$	--	$1\text{x}10^{-4}$
Cross-sectional flow area (m^2)	$8\text{x}10^{6}$	--	$8\text{x}10^{6}$
Hydraulic gradient	thermal	--	0.1 plus thermal
Drilling-direct hit of a canister (to land surface)			
Fraction of repository inventory affected	$4\text{x}10^{-6}$	$4\text{x}10^{-6}$	$4\text{x}10^{-6}$
Probability (yr^{-1})	$2.5\text{x}10^{-6}$	$2\text{x}10^{-5}$	$1\text{x}10^{-5}$
Drilling-does not hit canister (to land surface)			
Fraction of repository inventory affected	1.0	$6\text{x}10^{-5}$	1.0
Volume of repository water involved (m^3)	$2\text{x}10^{6}$	0.06	$2\text{x}10^{6}$
Volume of repository water released (m^3)	200.0	0.06	200.0
Probability (yr^{-1})	0.0025	0.02	0.01
Faulting (to surface water via aquifer)			
Fraction of repository directly disrupted	0.003	0.003	0.003
Fraction of repository inventory affected	1.0	0.05	1.0
Void volume of repository affected (m^3)	$2\text{x}10^{6}$	$1\text{x}10^{5}$	$2\text{x}10^{6}$
Permeability in fault zone flow path (m/yr)	3150.0	31.5	3150.0
Porosity in fault zone flow path	0.1	0.1	0.1
Cross-sectional area of fault zone (m^2)	4000.0	4000.0	4000.0
Hydraulic gradient	thermal	0.1 plus thermal	0.1 plus thermal
Probability (yr^{-1})	$2\text{x}10^{-8}$	$2\text{x}10^{-8}$	$5\text{x}10^{-7}$

Table B-4 (continued)

Reference Case Characteristics (SMC 82)

	Granite	Bedded Salt	Basalt
Breccia Pipe (to surface water via aquifer)			
Fraction of repository directly disrupted	--	0.004	--
Fraction of repository inventory affected	--	0.016	--
Permeability in breccia zone flow path (m/yr)	--	3150.0	--
Porosity in breccia zone flow path	--	0.2	--
Cross-sectional area of breccia zone (m^2)	--	3×10^4	--
Hydraulic gradient	--	0.1 plus thermal	--
Probability after first 500 yr (yr^{-1})	--	1×10^{-8}	--
Volcano (to air and land surface)			
Fraction of repository inventory affected	0.004	0.004	0.004
Probability (yr^{-1})	1×10^{-10}	1×10^{-10}	6×10^{-10}
Meteorite (to air and land surface)			
Fraction of repository inventory affected	0.001	0.001	0.001
Probability (yr^{-1})	4×10^{-11}	4×10^{-11}	4×10^{-11}

Normal Groundwater Flow

The rock surrounding a granite or basalt repository is permeable, and water moving through it could transport radioactive material to the overlying aquifer. The buoyancy effect resulting from the decay heat of the waste drives water through rock fractures in accordance with the permeability shown in Table B-4. In this model, water flows upward into the aquifer over the entire area of the repository and is replenished through fractures in the rock around the repository.

The release mechanism we considered for a bedded-salt repository is more complicated. Water may enter the repository from the upper aquifer through imperfections in the sealed openings, especially the main shaft seal. At the same time, plastic deformation of the salt caused by lithostatic pressure from the overburden eliminates these void spaces. This phenomenon tends to squeeze any water from the void spaces back up the shaft seals. If the canisters have failed, the water squeezed back up the shafts will contain some radionuclides from the waste. Contaminated water could then be released from the shafts into the overlying aquifer. However, in the situations we felt were likely, too little water leaked into the repository to cause any releases (ADL 79, SMC 82).

Drilling

Human intrusion (drilling) involves either a direct hit on the waste or intrusion into any water contacting the waste. A direct hit results in transportation of a fraction of the waste directly to the land surface and opens direct communication between the repository and aquifer(s) through the borehole. Release mechanisms for drilling intrusions into the water are similar to those for direct hits on the waste. For a granite or basalt repository, the material brought to the surface is a small fraction of the pool of contaminated water in the entire repository. For a bedded-salt repository, we assume that only one of a large number of small brine pockets around the waste would be affected. We further assume that intrusion into a brine pocket would cause ejection of the entire contents of the pocket directly to the land surface because of the high lithostatic pressure of the salt (ADL 79).

Faulting

Fault movement can open a high-permeability pathway for release of radioactive material to the overlying aquifer. The heat produced by the decaying radioactive material in the repository (thermal buoyancy) then drives the flow of water from the repository to the aquifer. In bedded salt and basalt, the hydraulic gradient between aquifers also affects the flow. In granite, recharge is from the surrounding bulk rock; in salt and basalt, recharge proceeds principally through the interconnection of the lower aquifer with the upper aquifer.

If waste is directly disturbed by the fault, radionuclides from damaged canisters can enter the water flowing to the aquifer at a rate that may be limited either by the release rate from the waste matrix or by the solubility of the radionuclides. Also, if canisters fail for other reasons--permitting radionuclides to leach or dissolve into the repository water--and a fault occurs later, this contaminated water can be transported to the overlying aquifer.

Breccia Pipes

A breccia pipe is a permeable formation resulting from the collapse of rock into cavities formed by the dissolution of underlying rock. Breccia pipes might occur near bedded salt-repositories, but they are not relevant to the other geologic media we studied. The release mechanisms to the overlying aquifer are the same as in faulting, but the flow area is larger than the flow area of the fault, and the permeability of the flow path is greater than that for faulting.

Meteorites and Volcanoes

Meteorites and volcanoes that disrupt a repository would pulverize parts of the repository and its host rock and would eject radioactive material into the atmosphere and onto the land surface. We assume that material ejected into the air would become uniformly mixed into the troposphere and would then settle onto the surface of the earth. Nuclides would reach people through the pathways previously described in Section B.1. Either type of event has an extremely small probability.

B.2.3 Reference Case Results

Table B-5 presents the projected number of fatal cancers resulting from the release of radionuclides by the release modes identified in Table B-4. For the bedded-salt repository, drilling events that miss the canisters but hit a brine pocket constitute the dominant type of initiating event, causing about 200 fatal cancers, primarily from releases of americium-241 (44 percent) and americium-243 (55 percent). For the granite repository, about 750 fatal cancers are projected in the first 10,000 years, due mainly to drilling into the repository water and to releases due to normal groundwater flow. The major causes of health effects are, again, americium-241 (10 percent) and americium-243 (89 percent). For all model repositories the risks from faulting, meteorites, volcanoes, and breccia pipes are insignificant. The dominant initiating event in the basalt repository is also drilling into the contaminated water in the repository; this could result in 3,000 fatal cancers over the 10,000 years, but releases from normal groundwater flow would add another 1,400 projected effects.

Table B-5

Projected Population Risks Over 10,000 Years: Reference Cases*

Projected Health Effects

Repository Type	Routine Release	Faulting	Drilling		Breccia Pipe	Volcano; Meteorite	Total
			(No hit)	(Hit)			
Granite	10	+	750	+	--	+	760
Bedded Salt	0	+	180	8	+	+	190
Basalt	1,400	3	3,000	2	--	+	4,400

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* From Table 7-4, SMC 82

# "No hit" means the drill does not hit solid waste but only repository water while "hit" indicates the drill does hit solid waste.

+ = Less than 1 projected fatal cancer

-- = not applicable

B.2.4 Sensitivity Analyses

To this point, we have examined our reference cases for calculating releases due to natural groundwater flow and several initiating events. Using our assumed values, our risk assessment estimated numbers of health effects for the reference cases. However, for a broader insight into the possible consequences of radionuclide releases to the biosphere, we have varied the values of several parameters of the repository models. These variations involved changes in canister life, different release rates (sometimes called "leach rates") from the waste form, different retardation factors for radionuclides in the aquifer, and different solubility limits of the radionuclides.

Different Canister Life and Waste Form Characteristics

We varied the values for canister failure time and waste matrix leach rate from the reference repository characteristics. The projected health effects in Table B-6 show the effect of these changes.

The primary effect of longer canister lifetimes is to lengthen the period over which risks from human intrusion and normal groundwater flow can be lowered or eliminated. Over 10,000 years, canister lifetime has much less effect on the health risk than does the waste-form release rate. There is a slight decrease in the risk value when increasing the canister lifetime from the reference age to 1,000 years. However, a canister lifetime of 5,000 years, rather than 1,000 years, significantly reduces the projected number of fatal cancers over 10,000 years.

Table B-6

Projected Population Risks Over 10,000 Years: Various Canister Lives and Waste Form Release Rates

	Projected Health Effects		
	Granite	**Bedded Salt**	**Basalt**
Canister Life			
Reference Case (100 years)	--	190	--
(500 years)	760	--	4,400
1000 years	575	90	3,900
5000 years	120	40	180
Waste Form Release Rate			
Reference Case (10^{-4} yr^{-1})	760	190	4,400
High Estimate (10^{-2} yr^{-1})	2,500	200	18,000
Low Estimate (10^{-6} yr^{-1})	10	50	50

-- = not applicable

Release-rate changes have much larger effects on the resulting risks than canister life changes, and release-rate changes have more effect for the granite and basalt repositories than for the bedded-salt repository. The risks for the bedded-salt repository do not increase much above those for a release rate of 10^{-5} parts of remaining waste per year (ppy) because of the solubility limits of the americium isotopes. Risks for the granite and basalt repositories do not increase much as the release rate increases above 10^{-3} ppy because there is no more waste to dissolve during the 10,000 years.

Finally, although not shown here, studies of simultaneously varying the waste matrix leach rate and canister lifetimes reinforced the previous observation that the leach rate has more effect on the overall risk than does the canister lifetime.

Solubility of Radionuclides

We examined the model repositories for unlimited solubility of all the radionuclides so that entry of all nuclides into groundwater would be limited only by the leach rate. Table B-7 shows that solubility limits are extremely important in limiting projected releases from the model repositories and resulting fatalities, especially for bedded salt. In the model bedded salt repository, the most significant solubility limit is that of the americium isotopes in brine pockets.

Table B-7

Projected Population Risks Over 10,000 Years: Various Retardation Factors and Solubility Limits

	Projected Health Effects		
	Granite	Bedded Salt	Basalt
Solubility Limits			
Reference Case *	760	190	4,400
No Solubility Limits	2,800	14,700	12,600
Retardation Factors			
Reference Case *	760	190	4,400
All Retardation Factors Equal to 1	38,000	200	5 million

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* see Table B-2

Retardation Factors in the Aquifer

Table B-7 also presents the projected health effects for two different choices of retardation factors: our reference case assumptions about retardation factors (see Table B-2), and a case that assumes that all retardation factors are equal to one (no retardation). Lower retardation produces many more health effects from expected releases or from faulting at granite and basalt repositories. Releases from bedded-salt repositories depend only slightly on retardation, because releases to an aquifer are much smaller than releases directly to the land surface.

Genetic Health Effects

In all types of repositories analyzed, the number of projected genetic effects are at least one order of magnitude less than the number of projected cancers, because most of the radionuclides involved do not concentrate in the gonads. For the reference case release modes--over 10,000 years following repository closure--we project 15, 2, and 150 genetic effects from releases from granite, bedded salt, and basalt repositories, respectively. In comparison, we project 760, 190, and 4,400 fatal cancers for these three repositories.

B.2.5 Conclusions

Several broad conclusions can be drawn from these performance assessments. First, major changes in the geochemistry at a site can affect long-term risks much more than major changes in the engineered barriers. For example, neglecting geochemical retardation for a granite repository increases the consequences from about 800 health effects to 38,000. In comparison, assuming that the waste form dissolves very quickly raises risks to a little more than 3,000, while assuming a zero lifetime for the waste canister increases risks only to about 1,000. Thus, it appears that efforts to identify a repository site with appropriate characteristics can have greater benefits than efforts to improve engineering controls.

Second, comparing the two types of engineering controls, variations of waste-form release rate consistently have more effect on long-term risks than variations of canister lifetime. Improvements in waste form appear to provide more benefits than improvements in waste canisters.

Finally, good engineering controls, particularly good waste forms, can overcome poor site characteristics. Our generic model of a basalt repository assumes that relatively large amounts of groundwater are available to dissolve and transport waste. In spite of this disadvantage, our basalt model can achieve risks comparable to those at the low end of the range for our granite model if the waste form used with basalt is about an order of magnitude better than that used with granite.

B.3 DOSE ASSESSMENT FOR INDIVIDUALS

We assessed the annual dose equivalent (hereafter referred to as annual dose, for convenience) that could be received by individuals who breathe contaminated air or drink contaminated water from a well drilled close to a repository. These pathways are less complex than those in the population risk assessment because they do not include the ingestion of foodstuffs or water from a river. We used the model repositories and geology described in Section B.1.2, and we examined several possible pathways through which individuals could be exposed. For each case, we calculated the annual doses to individuals and, for those cases involving releases through a borehole, the extent (i.e., area) of the aquifer that would be contaminated as a result of the releases. We chose four of the most significant scenarios to describe in this Appendix:

1. releases of solid waste to the land surface from striking waste while drilling;
2. releases to groundwater from striking contaminated repository water while drilling;
3. releases to groundwater from a fault movement that allows releases of water from within the repository, but that does not directly disrupt the waste and;
4. releases to the aquifer from natural groundwater flow.

The probabilities and consequences of the four initiating events differ markedly. Over 10,000 years, it is quite likely that someone will inadvertantly drill into a repository (assuming that institutional controls have no effect beginning 100 years after disposal), thereby opening a small pathway through which relatively small quantities of radionuclides could be released. Fault movement, on the other hand, is unlikely at a well-chosen site--but, if a fault should develop, it would open a large pathway through which large quantities of radionuclides could be released. Finally, natural groundwater flow is inevitable in the non-salt repositories beginning at the time of closure. However, the consequences will be small at an offsite well due to the slow movement of the radionuclides.

B.3.1 Pathway Characteristics

The preceding section described the events and processes we considered--for the individual dose analyses--that may allow radionuclides to reach an aquifer or the earth's surface. In this section we trace the pathways that those events and processes open from the waste to an individual.

Geospheric Pathways

Drilling. Drilling in search of resources will leave porous material in the resulting borehole through which contaminated water from the repository can flow. This contaminated water flows upward to the overlying aquifer mainly because of the heat produced by radioactive decay. In the cases of the basalt and bedded-salt repositories, it is assumed that the underlying aquifer is connected to the repository--resulting in a hydraulic gradient, which (conservatively) is assumed to drive water to the overlying aquifer. Upon reaching the aquifer, the contaminated water moves downstream from its point of origin, the borehole. Simultaneously, it very slowly spreads transversely across the aquifer, contaminating a parabolically shaped area. At some future time, according to our model, an individual might unknowingly drill a well within the contaminated area to obtain drinking water. At the time the person has ingested the water, the pathways caused by drilling are complete.

Faulting. The faulting event is postulated to open communication between the repository and an aquifer along a line that runs the full length of the repository--involving a much larger amount of radionuclides than drilling. The faulting event does not release radionuclides to the land surface, since we assume the implementing agencies would not permit selection of a site where an aquifer is under such pressure as to be artesian. (We also assume that the fault movement is much too small to transport radioactive waste directly to the surface.)

We assumed the fault would create a 10-meter wide zone of high permeability. The fault could cross the aquifer in any direction. A fault in the direction of the aquifer flow was chosen for analysis since it would produce the highest individual doses from faulting, because waste from many individual canisters along the fault would contribute to the dose rather than just a few if the fault were oblique to the canister row.

We considered two faulting scenarios. In one, the fault strikes and breaks a row of canisters; in the other, the canisters have failed before the fault develops, and the contents of two or more rows of failed canisters have combined in the porous volume of the repository backfill. However, only the pathway from a fault intersecting repository water is presented because these releases are much larger than releases restricted to direct effects on canisters. This pathway then terminates when the contaminated aquifer water is ingested by someone.

Normal Groundwater Flow. We also analyzed the natural groundwater flow pathway through the repository to the overlying aquifer. We looked only at the basalt repository, because this allowed us to estimate the upper-bound dose rate from natural groundwater flow. (The groundwater flow rate through the basalt repository is the greatest normal flow rate associated with any of the types of repositories we analyzed.) There is very little water flow through the bedded-salt repository since the plasticity of the salt allows it to seal cracks and fissures that may develop. In the case of the granite repository, there is no lower aquifer to produce a hydraulic gradient--so the only driving force to take nuclides to the overlying aquifer is the heat produced by the decaying waste.

Atmospheric Pathway

This pathway is straightforward and also is a result of drilling. Material reaches the surface either as a solid (a core sample) or a liquid (contaminated water from the repository).

The waste material brought to the surface may be removed by the drilling crew, it may be covered by other residue from the borehole, or it may lie at the top of the pile of residue. The latter scenario provides the most conservative estimate and is the one we used. The material is assumed to be a point source. We did not calculate the direct radiation dose from this release, which may be very large, because it depends on the way the material is handled, on the length of time the drillers remain exposed, and on other factors. We considered this incident to be an industrial accident not pertinent to this work. However, if the material becomes airborne it could be spread beyond the drilling site and could eventually expose people in the general population. In this analysis, the pathway ends when the material is inhaled and has exposed an individual's lungs. We also consider exposure from submersion in contaminated air and direct exposure from the contaminated surface; however, these doses were found to be very small compared to the inhalation pathway and are not discussed in this Appendix.

B.3.2 Dose Analysis

A computer code called MAXDOSE-EPA was used to perform the individual dose analyses (SE 81). The results of our study (GO 82) are complex because of the various pathways, the many variations of the parameters, and the number of data points corresponding to the variety of years after the initiating event for which we analyzed. Besides this, there is much data concerned with areas contaminated to various levels. Rather than attempt to summarize all of these results in this section, we present results for only those events that occur 1,000 years after the repository is sealed (except for shaft seal leakage that begins at 500 years, when the canisters fail). The method used to calculate the annual individual dose rates leads to a rate equal to the exposure in the 50th year of chronic exposure, which is how all our individual dose equivalent rates should be interpreted. Chapter 5 of Goldin, et al., (GO 82) presents the entire dose rate and contaminated land area results for the granite and bedded-salt repositories.

A drill that hits solid waste brings 15 percent of the waste of one canister to the surface. The largest dose rate is incurred by breathing contaminated air close to the drilling site (20 meters) 10 years after the event. The dose rate is about 11 rem per year (rem/yr) to the lungs, mostly from americium-241. At longer times after the drilling, plutonium-239 and -240 become dominant as the dose rates fall from about 4 rem/yr at 1,000 years after the event to about 20 mrem/yr at 10,000 years.

The same direct-hit drilling event will also allow nuclides to be released to the aquifer via the borehole. The largest dose rate from drinking contaminated aquifer water is about 600 rem/yr to red bone marrow, again 20 meters from the original point of release but 1,000 years after the event. No areas are contaminated enough to give more than 0.5 rem/yr until 1,000 years when americium-241 has traveled the 20-meter distance and contaminated 0.33 hectares (3,300 square meters). The contaminated area then increases to 6 hectares as the nuclides spread and, after 10,000 years, decreases because of radioactive decay.

Releases caused by a fault intersecting a granite repository are--as would be expected--much larger than those associated with drilling. The doses range from 40 rem/yr at 10 years and 20 meters from the repository to 3.4×10^5 rem/yr at 100 years and 20 meters. The latter dose rate slowly decreases after 100 years to 2,600 rem/yr at 10,000 years. Tin-126 dominates the dose rate for 20 years following the faulting event; americium-241 then dominates until 5,000 years, when americium-243 takes over. At 10,000 years, plutonium-239 delivers the greatest doses in this scenario--which is very unlikely to occur (see section B.3.3).

Doses from natural groundwater flow are not considered in MAXDOSE-EPA. Instead, we used an equation from section 4.1.1 of GO 82 to describe the release rate from the repository, and then we used equation 3-7 from the population risk assessment report (SMC 82) to relate the radionuclide flow rate from the repository to the nuclide flow rate at the well used for drinking water. We then related this flow rate to a radionuclide concentration and converted the concentration to a dose rate, using the dose conversion factors found in Table 3-4 of GO 82. The results of this analysis are presented in Table B-8. Within 100 meters of the repository there are potentially high dose rates. However, beyond 100 meters the potential annual doses are, with one exception, below 1 rem per year. The dominant nuclide close to the repository is americum-243 while cesium-135 generally dominates at greater distances--this is indicative of the longer half-life and greater mobility of cesium-135.

Table B-8

Dose Equivalent Rates (rem/yr) from Drinking Groundwater Contaminated by Normal Groundwater Flow Through a Basalt Repository

	Years after Closure			
Distance from Repository (m)	1000	2500	5000	10,000
20	1.5E+1* 94% Sn-126	1.5E+5 68% Am-243	8.5E+4 75% Am-243	3.4E+4 72% Am-243
100	1.5E+1 94% Sn-126	1.3E+1 94% Sn-126	1.0E+1 94% Sn-126	2.5E+4 70% Am-143
1000	9.8E-1 74% Cs-135	8.1E-1 78% Cs-135	5.9E-1 82% Cs-135	5.7E+0 94% Sn-126
2000	0.0E+0 0% None	8.0E-1 78% Cs-135	5.9E-1 83% Cs-135	3.3E-1 89% Cs-135
4000	0.0E+0 0% None	7.8E-1 80% Cs-135	5.8E-1 84% Cs-135	3.3E-1 90% Cs-135
8000	0.0E+0 0% None	0.0E+0 0% None	5.6E-1 87% Cs-135	3.2E-1 92% Cs-135
10,000	0.0E+0 0% None	0.0E+0 0% None	0.0E+0 0% None	3.2E-1 92% Cs-135
15,000	0.0E+0 0% None	0.0E+0 0% None	0.0E+0 0% None	3.1E-1 94% Cs-135
20,000	0.0E+0 0% None	0.0E+0 0% None	0.0E+0 0% None	0.0E+0 0% None

*1.5E+1 = 15 rem/yr
94% = 94% of the 15 rem/yr is from Sn-126.

B.3.3 Probabilities of Failure Modes

In this section we provide information useful for considering the probabilities of some of the potential individual doses just discussed. It should be noted, however, that the following probabilities of inadvertant human intrusion assume that all institutional controls--both active and passive--will be ineffectual beginning 100 years after disposal. Thus, we believe that these probabilities for human intrusion may be conservatively high.

Direct Hit on Waste

From the information given in the ADL report (ADL 79), the probability of a drill hitting a waste canister is estimated to be 2×10^{-5} hits per year in a bedded-salt repository, 3×10^{-6} hits per year in a granite repository, and 1×10^{-7} hits per year in a basalt repository.

Drilling into Contaminated Repository Water

According to the ADL study (ADL 79), the frequency, and therefore the probability, of drilling into the granite repository is once every 400 years, or 2×10^{-3} per year. The probability of drilling into a basalt repository is given as 1×10^{-2} per year. The probability of drilling into a brine pocket in a salt repository may be conservatively estimated to be the same as the drilling frequency into any part of a salt repository--even though it would likely be lower because brine pockets do not exist throughout the repository. However, using the more conservative approach, ADL estimated 21 drilling attempts in the first 1,000 years--which results in a probability of 2×10^{-2} hits per year.

Fault Movement

ADL (ADL 79) sets the probability of a fault occurring as $2\text{x}10^{-8}$ per year for bedded salt and granite and $5\text{x}10^{-7}$ per year for basalt. However, we believe that only 10 percent of the faults would be lengthwise (i.e., parallel or within 18 degrees of the longest repository axis). These would produce the effects studied here, but there is a 90 percent probability that the effects would be less than those given here.

B.3.4 Probability of Exposure

Air

The area around the point where the waste material is brought to the surface following a direct hit on a waste canister--where the air and ground are contaminated enough to result in a level of 500 mrem/yr--was found to have a radius of 170 meters. Since the radioactivity persists for hundreds or thousands of years and the radioactive material is assumed not to be reburied, it is virtually certain that someone would eventually encounter some small level of exposure.

Water

The probability of a person encountering a contaminated area of the aquifer can be estimated by the probability of drilling for drinking water in the contaminated area, the area of the contamination, and the length of time the area will remain contaminated. There is no simple way to display the many results of these calculations; however, an example will illustrate the procedure.

As was discussed in Section 5.3 of this document, the average well drilling density in the United States is 6.4×10^{-4} well per hectare per century. Through calculations performed by the computer code MAXDOSE-EPA, it was found that the area contaminated above 500 mrem/yr at 10,000 years is 8 hectares. The probability of a well being drilled into the contaminated area is then (6.4×10^{-4}) times 8 -- or about 5×10^{-3} per year.

B.3.5 Conclusion

Considering the failure model probabilities and the associated dose equivalents, we conclude that the chance of individuals receiving large doses from disruptive events in a repository is small.

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